FUZZY LOGIC CONTROL OF STRATIFICATION OF PARTICLES DURING JIGGING

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CERTIFICATE

11-6-97

It is certified that the work contained in the thesis entitled "Fuzzy Logic Control of Stratification of Particles during Jigging", by Mr P V Kishore has been carried out under my supervision and this work has not been submitted elsewhere for a degree

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Dedicated to
my Parents

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Abstract

Jigs are one of the most important equipment used in stratification of mineral particles, under the influence of hydrodynamic and gravitational forces Very little is known about the mechanism taking place in a jig which results in separation of particles Many theories were proposed by researchers regrading the stratification process taking place to understand the complex mechanism Currently, research is still being done to have a better understanding of the mechanism of the process in order to achieve better yield and improved recovery at competitive costs

It is believed that the above research goals can be achieved through proper control of the process In absense of a thorough knowledge of the process a control technique based on fuzzy logic is considered This technique relies on the intuitive knowledge of the process operator and do not take into consideration the micro-events leading to complete stratification A process simulator based on discrete element is used to compensate for the intuitive knowledge of the operator In other words, the actual process is replaced by a mathematical model and extensive simulation is done for system learning In particular, influence of process parameters such as frequency and amplitude of pulsation on the degree of stratification is analyzed This information is transalated to several fuzzy rules Finally, based on these rules the controller is tested

The controller performance is assessed by comparing simualtion results under different situations The results of simulations show that the controller is able to drive the stratification of particles at a faster rate and is also able to stop the process when the desired degree of stratification is achieved This research has shown the potential of application of fuzzy logic control to jigging for improved productivity

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Chapter 1

INTRODUCTION

Jig is one of the oldest separation units used in mineral processing for separation of minerals from gangue The principle of jigging was discovered by an Egyptian craftsman in a very interesting manner He was trying to wash a pile of stones that were dirty He put the stones in a basket and tied it with a rope that hung over a pulley located on a pole When the basket was moved up and down in the river the craftsman observed that not only the stones were washed but they were sorted out according to colors What really happened was that the stones of different density possessed different colors and hence the stones were getting separated according to their color This aspect of separation of particles based on density is what is practiced in jigging

Jigging is a process in which separation of particles is achieved based on difference in specific gravity and size This separation is accomplished by the motion of water through a bed of particles which produces a pulsating current causing the bed to move This movement is a result of en-masse motion of individual particles comprising the bed Due to the difference in the density of particles, individual particle movement differ as the buoyancy and drag forces acting on the particle are different Over a period of time these differences in forces add up and the particles tend get separated This, explanation however, is far from simple

There are many theories used to understand the principle of jigging The theory that is most commonly used to describe jigging is one that was proposed by Gaudin [1] This

theory considers the following three major effects that lead to a stratified bed

1 Differential acceleration

2 Hindered settling

3 Consolidation trickling

1.1 Mechanism of Jigging

1 1 1 Differential acceleration

The motion of jig bed can be achieved by using either a fixed sieve jig and pulsating the water or by employing a moving sieve in stagnant water When the motion is transferred from sieve to bed dilation of bed takes place The equation of motion of a particle settling in a viscous fluid is

$$my = mg - m^1 g - D \tag{1 1}$$

where m is the mass of the mineral grain, y is the acceleration, g is the acceleration due to gravity, m^1 is the mass of displaced fluid, and D is the fluid resistance due to particle movement At the beginning of the particle movement, since velocity is very small D can be ignored as it is a function of velocity Therefore,

$$y = (\frac{m - m^1}{m})g = (\frac{\rho_s - \rho_f}{\rho_g})g \tag{1 2}$$

where ρ_s, and ρ_f are the specific gravities of the solid and the fluid respectively Thus, the differential initial acceleration is dependent on the densities of the solid and fluid Theoretically, if the duration of fall is short enough and the repetition of fall is frequent enough, the total distance travelled by the particles will be affected more by the differential initial acceleration i e , by density In other words, to separate small and heavy mineral particles form large and light particles short jigging cycle is necessary The effect of differential initial acceleration[2] is shown in figure 1 1

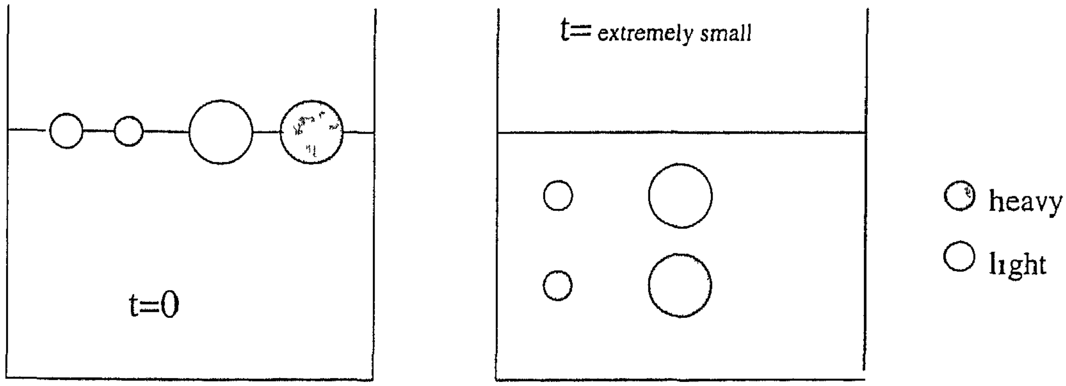

Figure 1 1 Differential acceleration

1 1 2 Hindered settling

When the jigging is carried for a longer time the particles attain terminal velocities and move at a rate dependent on their specific gravity and size Since the particle bed is a loosely packed mass, the particles under these conditions are said to be settling under hindered settling condition Under this condition, particles influence one another by means of their respective velocity fields Moreover, the density of the fluid is a slurry density, and this is the density of the medium through which particles are moving Hindered settling has a marked effect on the separation of coarse minerals, for which longer and slower strokes should be used, although in practice, with coarser feeds, it is improbable that the larger particles have time to reach their terminal velocities Figure1 2 shows the effect of hindered settling[2] on the separation

1 1 3 Consolidation trickling

At the end of pulsation stroke as the bed begins to compact, the large particles interlock Thus a void structure is created where the voidage is proportional to the size distribution of particles In this state the fine particles find their way through the voidage while the coarser particles remain locked The motion of these fine particles is purely due to the influence of gravity alone This phase is called consolidation trickling This phase can be

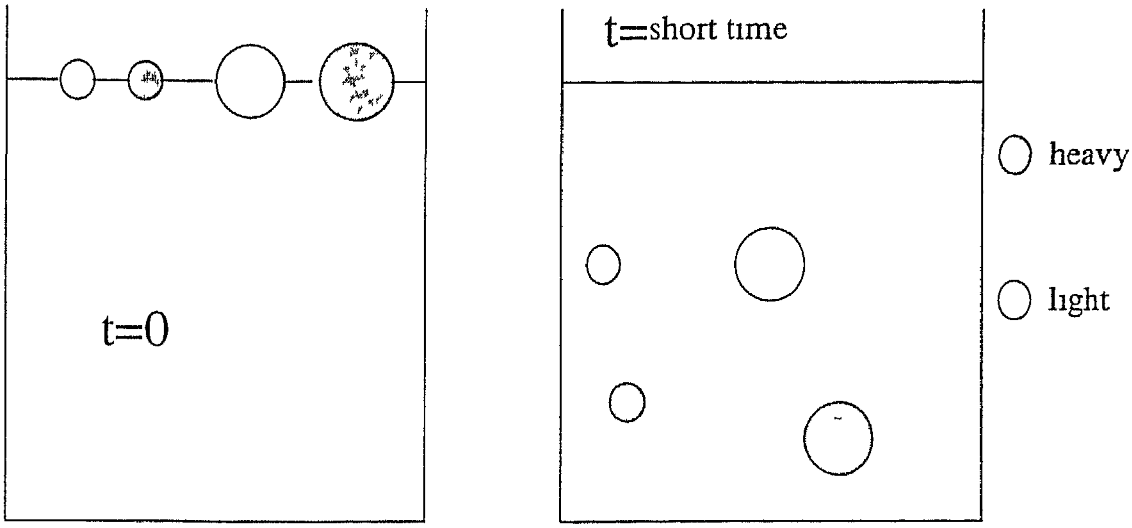

Figure 1 2 Hindered settling

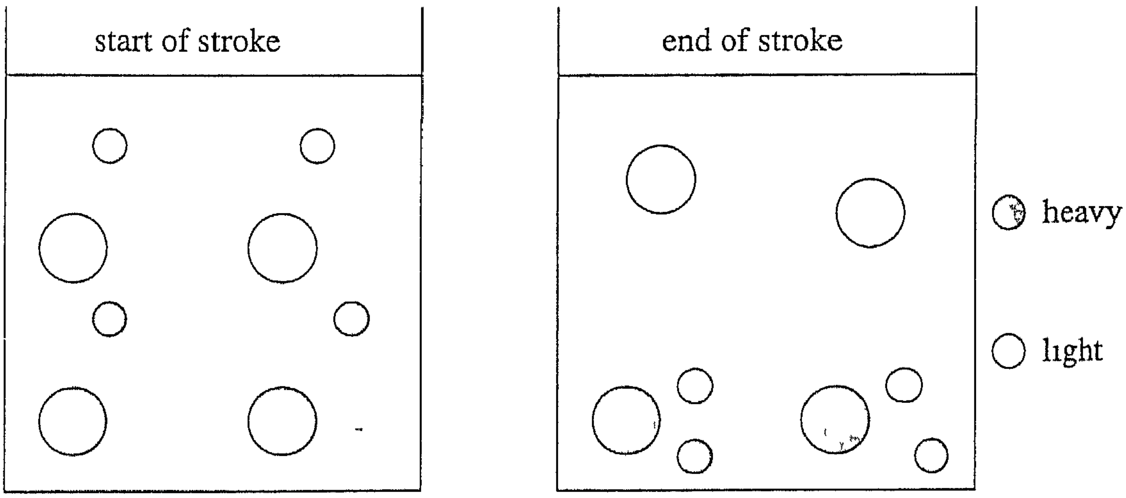

Figure 1 3 Consolidation trickling

made to last long especially in the recovery of fine heavy minerals by increasing the period of suction part of the pulsation cycle Figure1 3 shows the effect of consolidating trickling[2]

The simplified explanation given above to describe the jigging process is far from realistic as a host of other factors influence the process Some of these factors that influence the process are feed properties, operational parameters such as amplitude and frequency of pulsation, design of the jig, etc In order to understand the process, all these factors need to be considered and this forms the basis of discussion of next chapter

1.2 Jigging Practice

There are various types of jigs used in the industry for specific applications These can be classified based on the manner in which the jig operates as given below[8,9,10]

- Type of sieve used i e ,fixed or moving
- Medium used i e , air or water
- Type of plusation applied i e , pulsation by piston, or by compressed air

In parctice Baum and Batac jigs are most commonly used jigs in practice for coal cleaning where plusation is done by compressed air The basic difference between Baum and Batac jig[8] is that in Baum jig air chamber is placed to the side while in Batac jig the air chamber is placed beneath the washing bed In Batac jig, this was done to remove the limitation in width specific to Baum jig However in both types of jigs Here the motion of the fluid is caused by controlling the air pressure Minerals are separated by the use of plunger type jigs where a plunger is used to move the fluid

Consider the operation of a jig where the fluid is pulsated by means of air pressure adjustment as in the case of a Baum or Batac jig A schematic of this jig is shown in figure 1 4 Initially, the pressure is allowed to build in the air chamber to the desired level At this stage the valve located in the air chamber opens such that the air chamber is directly connected to the U-shaped jig chamber The water having experienced this pressure gushes through the particle bed causing the bed to dilate At this time, the air chamber is closed and the valve opens to the atmosphere The water by virtue of its inertia falls back through the bed and eventually maintains a level between the two legs of the U-shaped jig chamber While doing so, the falling fluid brings the particle bed to a compacted stage This operation is repeated for several cycles till a desired degree of stratification is obtained

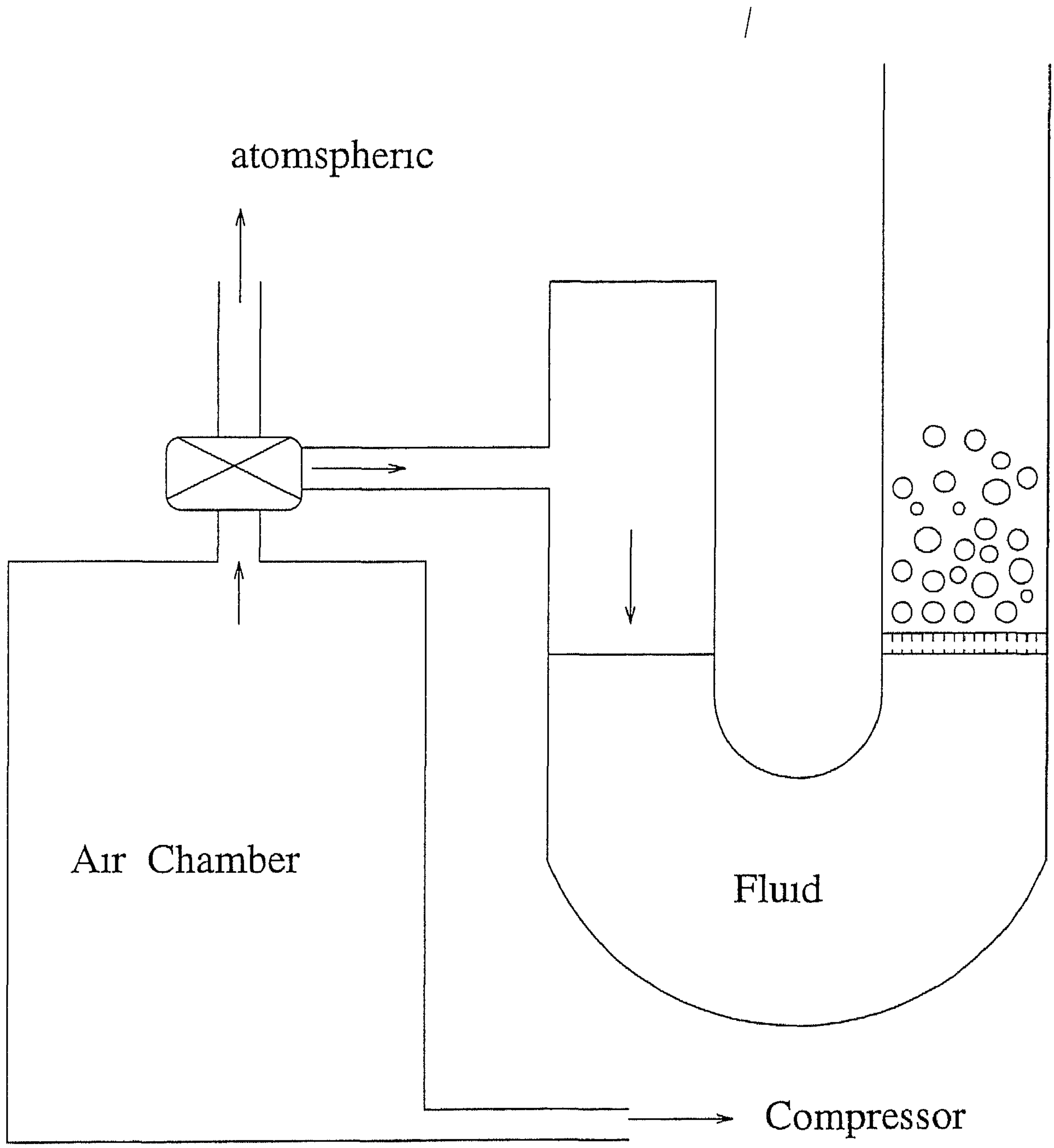

Figure 1 4 A typical jig equipment

Analyzing the above operation, it may appear that the motion of fluid is synchronous to that of air However, careful experimental data of Lyman [3] show that considerable amount of phase lag exists between the motion of air and water In order to illustrate this idea further, data corresponding to a typical Mayer's cycle is presented in figure 1 5 for a Baum jig This figure shows the variation in the air pressure in one side of the U-shaped jig with the water velocity in the jigging chamber during one jig cycle At the beginning of the cycle, when the air valve is open to the atmosphere, water falls in the jigging chamber, thus the back pressure in the other leg of U-shaped chamber increases rapidly This rise in pressure causes the water level to move upwards in the jig chamber and then it moves rapidly as the inlet valve is connected to the air chamber located under the jig Thus the response of water to the air valve settings is complex in the sense that the pulsion and suction do not coincide with the opening and closing of the air valve

The inherent nonlinearity and the complex nature of the process give rise to several practical problems One such problem is to control the process such that the best separation is achieved at an acceptable rate of production Controlling such processes which are non-linear and complex is quite difficult A recent Australian work by Rong & Lyman[4] does indeed point out that there is considerable room for control for jigging via modern day high speed desk top computer

In a novel approach to control such complex processes one would investigate the control strategies employed by human operator In many cases the process operator can control a complex process more effectively than an automatic system Such analysis which takes into consideration the experience of human operator is *fuzzy logic* The basic idea behind this logic is to incorporate the experience of human operator in the design of controller This is because human operator knows what type of control to be used for typical process dynamics so as to produce better results by his experience

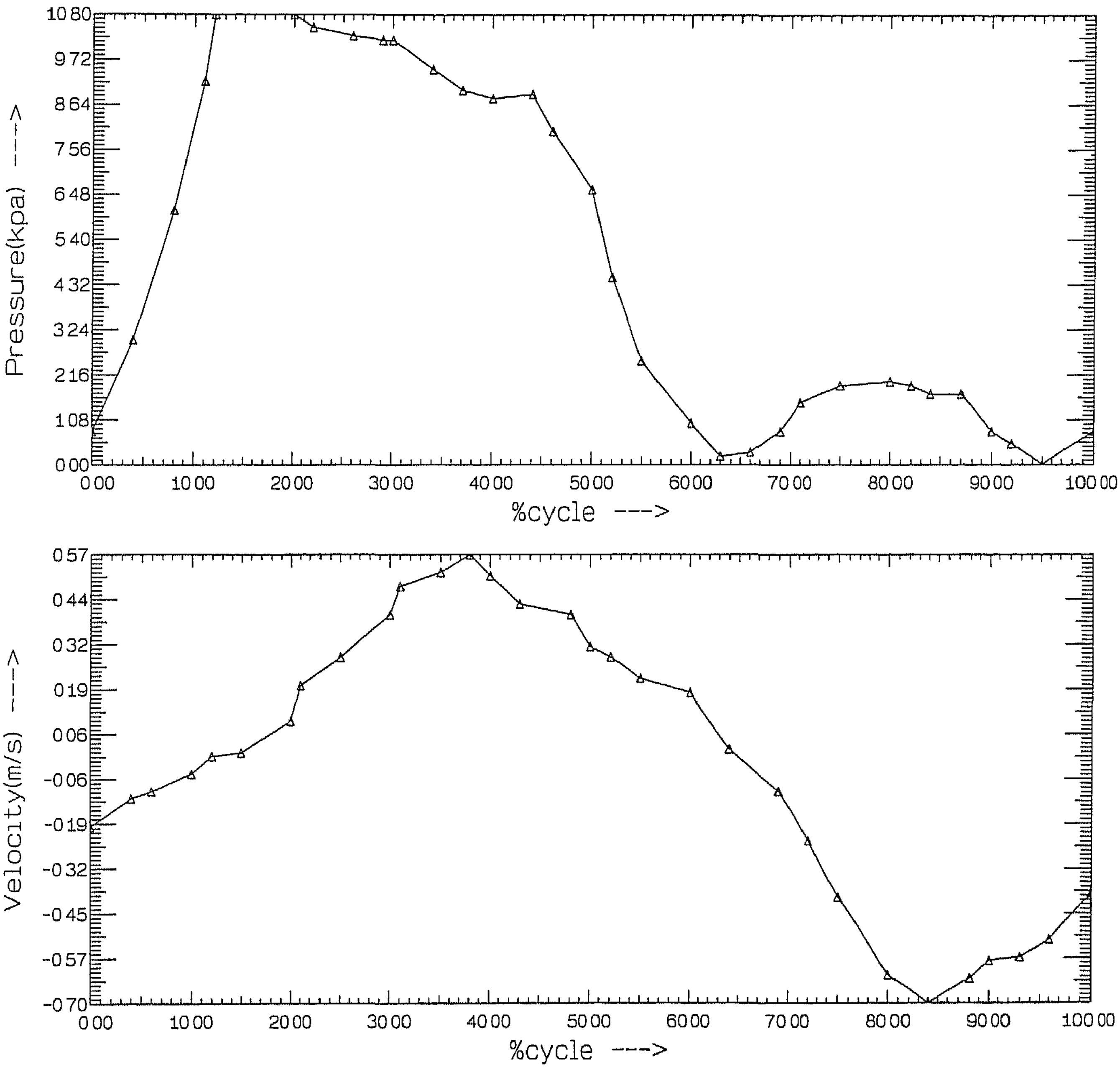

Figure 1 5 Variation of pressure and velocity within a jig cycle

Fuzzy logic control has steadily gained acceptance and popularity among scientific community This technique is applied by the use of fuzzy rules which are formulated by analysing the human experience In the present work, a mathematical model is used to study the system behavior The knowledge gained is incorporated into a set of rules that are used for the control of the process The purpose of this research is to investigate and explore the possibility of implementing fuzzy logic control to monitor stratification of particles in a jig bed

The thesis is divided into several chapters A discussion on various mathematical models available in the literature to describe the jigging process is given in Chapter 2 with particular emphasis on one of the most recent model based on potential energy principle Also, the discrete element model that is used to study the system behavior is discussed Chapter 3 is focused on the theory of fuzzy logic control Results of numerical simulation is presented in Chapter 4 Finally, the conclusions made based on the present investigation and the scope for future work is discussed in Chapter 5

Chapter 2

JIG MODEL

2 1 Introduction

A process can be easily understood without the experience of it by the knowledge of a mathematical model which describes it Jigging process is no exception There are various models that are proposed by several researchers to explain the process There are also various theories which explain the stratification process taking place during jigging All the theories explaining the stratification process during jigging can be classified into six categories as

1 classical theory

2 potential energy minimization theory

3 dispersion model of particle suspension

4 energy dissipation theory

5 stochastic analysis

6 empirical models

There are excellent review papers available in the literature that explain the above theories in detail [1,5,6] These review papers point to the need for a more unified theory that best describes the stratification process taking all operational and design parameters

into consideration. One such approach is the Discrete Element Method (DEM)[17]. In this chapter we review the model developed by Tavares and King [7] based on potential energy theory and the discrete element method that is extensively used in this research work. Furthermore, the results obtained by using both the models is compared.

2.2 Tavares-King Model[7]

This model predicts the concentration profile in a jig bed. The method used to calculate the stratification profile is based on the potential energy theory of Mayer[6] who showed that under ideal conditions a bed of particles will stratify in such a way as to minimize the gravitational potential energy of the bed. An unstratified bed can be assumed as an unstable system having potential energy gradient. This system tries to go to equilibrium by decreasing the potential energy to minimum value. It would be stable by completely stratifying itself into different layers according to difference in density and size. In practice, this ideal stratification is never achieved because of various dispersive forces that are present which tend to disperse the particles and thus destroy the ideal stratification profile. The actual stratification achieved represents a balance between the stratification forces and the dispersive forces. Based on the above ideas Tavares and King developed the jig model for multi component mixtures as explained below.

Consider a packed bed of monosize spherical particles whose densities vary over a wide range. The gradient of the potential energy of a particle of density ρ in a bed of particles of average density $\overline{\rho}$ is given by

$$\frac{dE}{dH} = gV_p(\rho - \overline{\rho}) \tag{2.1}$$

where V_p is the particle volume, E is the gravitational potential energy, H is the height of the particle in the bed measured from the bedplate. The average density of the particles $\overline{\rho}$,

at height H is given by

$$\overline{\rho} = \int_0^\infty \rho C_p d\rho \tag{2 2}$$

where C_p is the volumetric concentration of particles within the solid phase with density ρ at height H The potential energy gradient causes a particle to migrate upward or downward in the jig bed depending on the sign of $\rho - \overline{\rho}$ If $\rho\overline{\rho}$ the particle will move down and vice-versa The movement of particles in the bed is proportional to potential energy gradient so that the flux of particles of density ρ due to the potential energy gradient is given by

$$n_s = -C_p u \frac{dE}{dH} \tag{2 3}$$

where n_s is the stratification flux and u is the specific mobility of the particle which is defined as the penetration velocity achieved by a particle in the absence of any dispersive forces under a unit potential energy gradient Substituting (2 1) in (2 3) gives

$$n_s = C_p u g V_p(\rho - \overline{\rho}) \tag{2 4}$$

Opposing the stratification flux, there is the diffusive flux due to particle-particle and particle-fluid interactions It is described by a Fickian equation of the type

$$n_D = -D\frac{dC_p}{dH} \tag{2 5}$$

The diffusion constant D in Equation(2 5) is dependent on the particle size, shape and bed expansion mechanism

The ideal Mayer stratification profile[6] that minimizes the potential energy of the bed will never be achieved in practice A dynamic state of equilibrium of the bed will be established when the stratification flux for each particle type is exactly balanced by the corresponding diffusive flux The condition is defined by

$$n_D = -n_s \tag{2 6}$$

so that,

$$\frac{dC_p}{dH} = -\frac{ugV_p}{D} C_p(\rho - \overline{\rho}) \tag{2 7}$$

The solution to differential equation (2 7) gives the vertical concentration profile of monosize particles of density ρ No boundary conditions can be specified apriori for equation (2 7) because it is not possible to specify the concentration of any species at either the top or bottom of the stratified bed Solutions to equation (2 7) must satisfy the following conditions

$$\int_0^1 C_p dh = C_p^f \qquad forall \rho \tag{2 8}$$

$$\int_0^1 C_p d\rho = 1 \qquad 0 \leq 1 \tag{2 9}$$

where C_p^f is the feed density distribution by volume Equations (2 8) and (2 9) are sufficient to define the solution to equation (2 7) without any other boundary conditions

A more convenient, density discrestized form of the model for n components is expressed by

$$\frac{dC_i(h)}{dh} = -\alpha C_i(h)[\rho_i - \overline{\rho}(h)] \qquad i = 1, 2, \quad n \tag{2 10}$$

where $C_i(h)$ is the volume fraction at height h of material characterized by density ρ_i The representative density of each interval ρ_i corresponds to the mean density of each class Considering the lack of information at both ends of the density spectrum, particularly of the last sinks fraction, the mean densities of those intervals are usually known approximately The average solids density at level h is given by

$$\overline{\rho}(h) = \sum_{i=1}^{n} C_i(h)\rho_i \tag{2 11}$$

The system of equations defined by equations (2 10) must be solved subject to

$$\sum_{i=1}^{n} C_i(h) = 1 \qquad 0 \leq h \leq 1 \tag{2 12}$$

$$C_i^f = \int_0^1 C_i(h)dh \tag{2 13}$$

In order to determine the equilibrium concentration profile it is necessary to solve the system of n coupled differential equations differential equations defined by equation (2 10) subjected to equations (2 12) and (2 13) A very efficient procedure for integrating the equilibrium equations was developed using the following iterative method Intergration of the stratification equations (2 10) from the bottom of the bed with the unknown initial condition $C_i(h) = C_i^0$ gives

$$C_i(h) = C_i^0 exp[-\alpha\rho_i h + \alpha\int_0^h \overline{\rho}(u)du] \tag{2 14}$$

Substituting equation (2 14) into equation (2 13)

$$\int_0^1 C_1^0 exp[-\alpha\rho_i h + \alpha\int_0 \overline{\rho}(u)duh]dh = C_i^f \tag{2 15}$$

and rearranging gives an estimate of the concentration of each species at the bottom of the bed

$$C_i^0 = \frac{C_i^f}{\int_0^1 exp[-\alpha\rho_i h + \alpha\int_0^h \overline{\rho}(u)du]dh} \tag{2 16}$$

An initial average density profile $\overline{\rho}(h)$ is assumed, each C_i^0 is calculated using equation (2 16) and normalized to satisfy

$$\sum_{i=1}^{n} C_i^0 = 1 \tag{2 17}$$

New concentration and average density profiles are calculated from equations (2 14) and (2 11) and the procedure is repeated until convergence

One of the major drawbacks of this model is that it works only for the monosize particles and can only describe the initial and final state of the system In othere words, the model cannot predict the dynamics of the process Another problem associated with this model is the relation between the process parameters and the degree of stratification This relationship is brought about through a parameter called "α" It requires enormous amount of data to establish a correlation between degree of stratification and the process parameters through α It is particularly quite cumbersome to achieve this by experimental means It is shown here that with the help of the DEM model this task is easily achieved

2 3 Discrete Element Approach to Jigging[11]

The discrete element method (DEM) is a numerical scheme pioneered by Cundall and Strack[12] for simulating the behavior of systems of discrete interacting bodies It has gained popularity over the past decade in several areas of engineering where behavior of particulate material had to be studied taking an alternate route to continuum approach This scheme allows finite displacements and rotation of discrete bodies, where complete loss of contact and formation of new contacts take place as the calculation progresses The program 2DMILL developed by Mishra[11] implements the DEM algorithm for two-dimensional disc-shaped bodies, it has been used to study ball mill problems In the current work this code is modified to a great extent to adapt the code for the simulation of particle motion in jigs

2 3 1 The Algorithm

The algorithm of the computer code employed here is conceptually very simple Every disc in the assembly is identified separately, with its radius, mass, moment of inertia and contact properties For every disc, calculations are made to maintain a list of the discs which are in immediate contact and in the near neighborhood The amount and the rate of overlap between discs are used to determine the normal and shear forces Then the contact forces

on a disc are added to get the net out-of-balance force acting on it This unbalanced force is then used to estimate each disc's current acceleration, which is integrated in turn for the velocity and displacement at the next instant in time

The numerical scheme adopted in the DEM formulation applies Newton's second law to the discs and a force-displacement law at the contacts Newton's second law gives the motion of the discs resulting from the forces acting on them The forces developing at the contacts are modeled by pair of normal and tangential spring-dashpots at every contact point The form of this contact is illustrated in the figure2 1 The provision of viscous-contact damping models the system realistically, because the coefficients of restitution for different contacts are used to compute the damping constants Also, friction damping occurs during sliding when the absolute value of the shear force at any contact exceeds a maximum value found by the product of the normal force at the contact and the coefficient of friction

The dynamic equilibrium equations can be written for a disc characterized by displacement x, mass m, and moment of inertia I as

$$m x_i + C_i x_i + K_i x_i = F_i \qquad i = 1,2 \tag{2 18}$$

$$I\theta + \sum_{i=1}^{2}(K_i x_i + C_i x_i)s_i = M \tag{2 19}$$

where F_i is the force acting in the direction i, M is the moment about the centroid of the disc, and s_i is the perpendicular distance from the line of action of the force $(K_i x_i + C_i x_i)$ to the centroid of the ball The parameters K and C are the spring and dashpot constants, respectively The directions i=1 and 2 refer to the coordinate axis

The above two equations are a special case of the second-order nonlinear differential equation of the following form

$$x + ax = 1/mF(i, x) \tag{2 20}$$

The quantity $F(x, x)$ is the force generated from contact and other applied forces During a

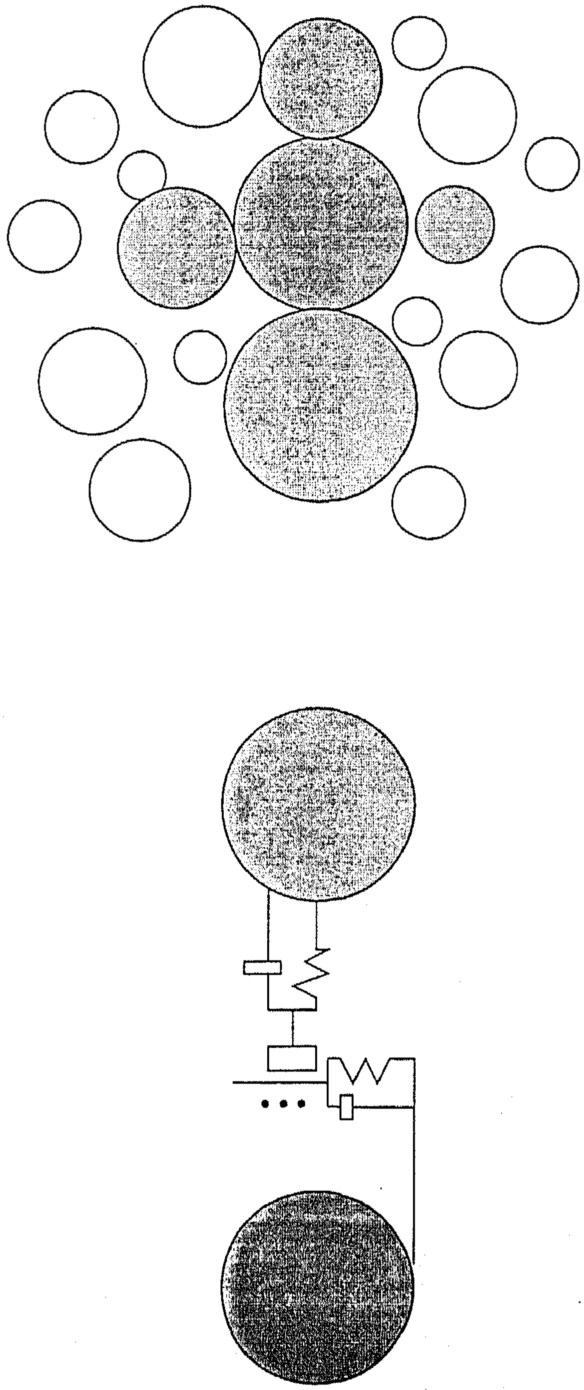

Figure 2.1: Representation of a contact.

small time step t to t+δt, this equation can be integrated by finite difference approximations of the derivatives

$$x = \frac{x(t+\delta t) - x(t)}{\delta t} \tag{2 21}$$

$$x = \frac{x(t+\delta t) + x(t)}{2} \tag{2 22}$$

Substitution of Eq 2 21 and Eq 2 22 into Eq 2 20 results in a simple equation that can be solved for the velocity during time step t to $t + \delta t$ This velocity is then used to find displacements and rotation of the discs by a further numerical integration

$$x(t+\delta t) = x(t) + x(t+\delta t)\delta t \tag{2 23}$$

Thus, by repeating this calculation for each disc, the new position of all the discs is determined and, by repeating the entire set of calculation at successive time steps, gives the movement of the charge in the x,y-coordinate space

In the spring-dashpot model, for the calculation of the normal and shear forces, a linear elastic behavior of the springs is assumed (F = Kx), whereas the force in the dashpot is proportional to the relative velocity of the colliding bodies The proportionality constants, that is, the stiffness and the damping constant, determine the time step with which calculation will proceed The integration scheme outlined above is a central difference scheme, the stability of this numerical scheme depends on the time step chosen The time step that may be used to assure numerical stability is given in terms of the mass and the stiffness of the smallest disc as

$$\delta t < 2\sqrt{m/K} \tag{2 24}$$

Based on this stability criterion, the critical time step is evaluated Failure to ensure this condition will result in violation of the principle of conservation of energy Energy is

dissipated in the model through friction, contact, and global damping The energy input to the system between two time steps is given

$$E = \int_1^2 (F_{damping} + F_{friction})\, dr \tag{2 25}$$

The effect of fluid on the motion of particles is computed in a simplified manner When a particle enters the fluid its Reynolds number(Re) is computed Then the drag coefficient is determined by using Abraham equation

$$C_d = 0\ 28(1 + \frac{9\ 06}{\sqrt{Re}}^2) \tag{2 26}$$

where C_d is the drag coefficient The above equation is generally valid for $Re < 10^5$ For higher Reynolds number a constant value of 0 44 is chosen The force on the particle due to the viscous drag is given by

$$F_d = 0\ 5 \times C_d \times \rho_f \times \nu^2 * A \tag{2 27}$$

where F_b is the force due to buoyancy effect, m is the mass of the ball, ρ_s is the density of ball, and g is the acceleration due to gravity All the forces are added and the position of the position of the particles are found by numerical integration as discussed earlier The energy supplied between two time steps to move the particle over a distance $d\nu$ is as follows

$$E = \int (F_{drag} + F_{friction} + F_{damping})\, d\nu \tag{2 28}$$

This when summed over all particles and time steps results in the net energy dissipated during stratification

2.4 Numerical Simulation

Study of variation of concentration profiles of different types of particles differing in their density and size is done with the help of DEM model and Tavares and King model[7]

Three types of particles differing in size and density are taken The specifications of the particles is shown in table 2 1

By using the code developed based on DEM model the concentration profiles at different bed heights are drawn The variation of concentration profiles of the three types of particles is shown in figure 2 2 As it is seen in this figure that the concentration profiles are intuitively correct for a bed that is stratified In other words, the concentration of heavier particle is maximum at the bottom of the bed and conversely, the concentration of lighter particles is maximum towards the end of the bed

Concentration profiles for different particles differing in density are analysed with Tavares and King model[7] A computer program is written to slove the model equations A flow sheet of the code developed is shown in figure2 3

Different concentration profiles can be drawn for different values of α However, for the comparison purpose only one particle type is chosen which is the heaviest particle type Various concentration profiles are drawn for different values of α The curve which matches with the DEM model is used to estimate α In this manner α was found to be 0 009 Comparative results are shown in figure 2 4 Thus, it has become possible to relate the degree of stratification to the operating parameters such as amplitude and frequency of pulsation through α Therefore using Tavares-King model[7] for simulation at the above pulsation rate there is no need to find the α value as it is established through the DEM

Table 2 1 Specifications of three types of particles used in the simulation

Size radius(m)	Density kg/m^3	Mass kg	No of particles
0 031	3500	0 4363	145
0 0325	2200	0 3161	145
0 0351	1500	0 2716	145

model[11]

A computer code ıs avaılable to have an vıew of dıfferent partıcle posıtıons at dıfferent ınstants of tıme obtaıned by DEM model Snapshots of these concentratıon profiles are shown here Fıgure2 5 and 2 6 show the concentratıon profiles of three partıcles done wıth DEM model at 0 14-m amplıtude and 16cycles/sec Fıgure 2 5 shows the begınnıng vıew of the bed before stratıficatıon and figure 2 6 shows the end vıew

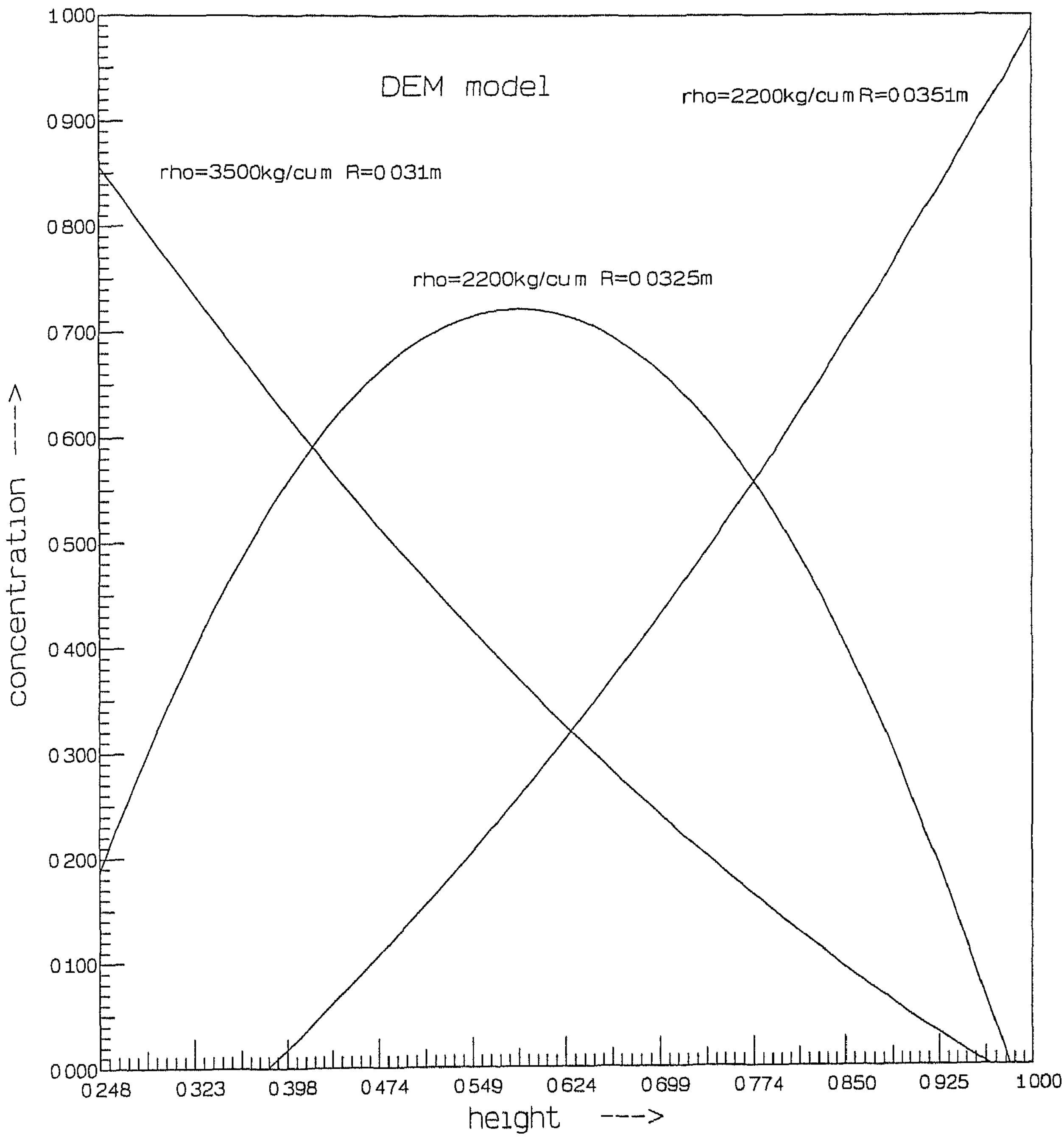

Figure 2 2 Plot showing concentration profiles of the particles in jig

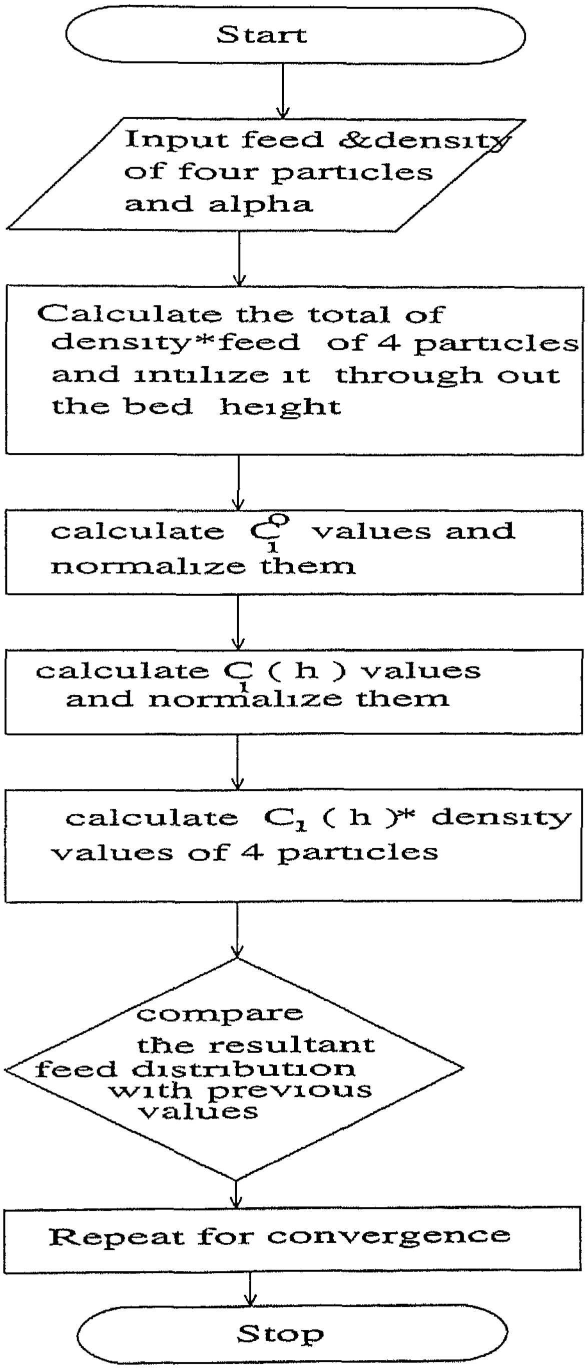

Figure 2 3 Flowsheet of Tavares and King model

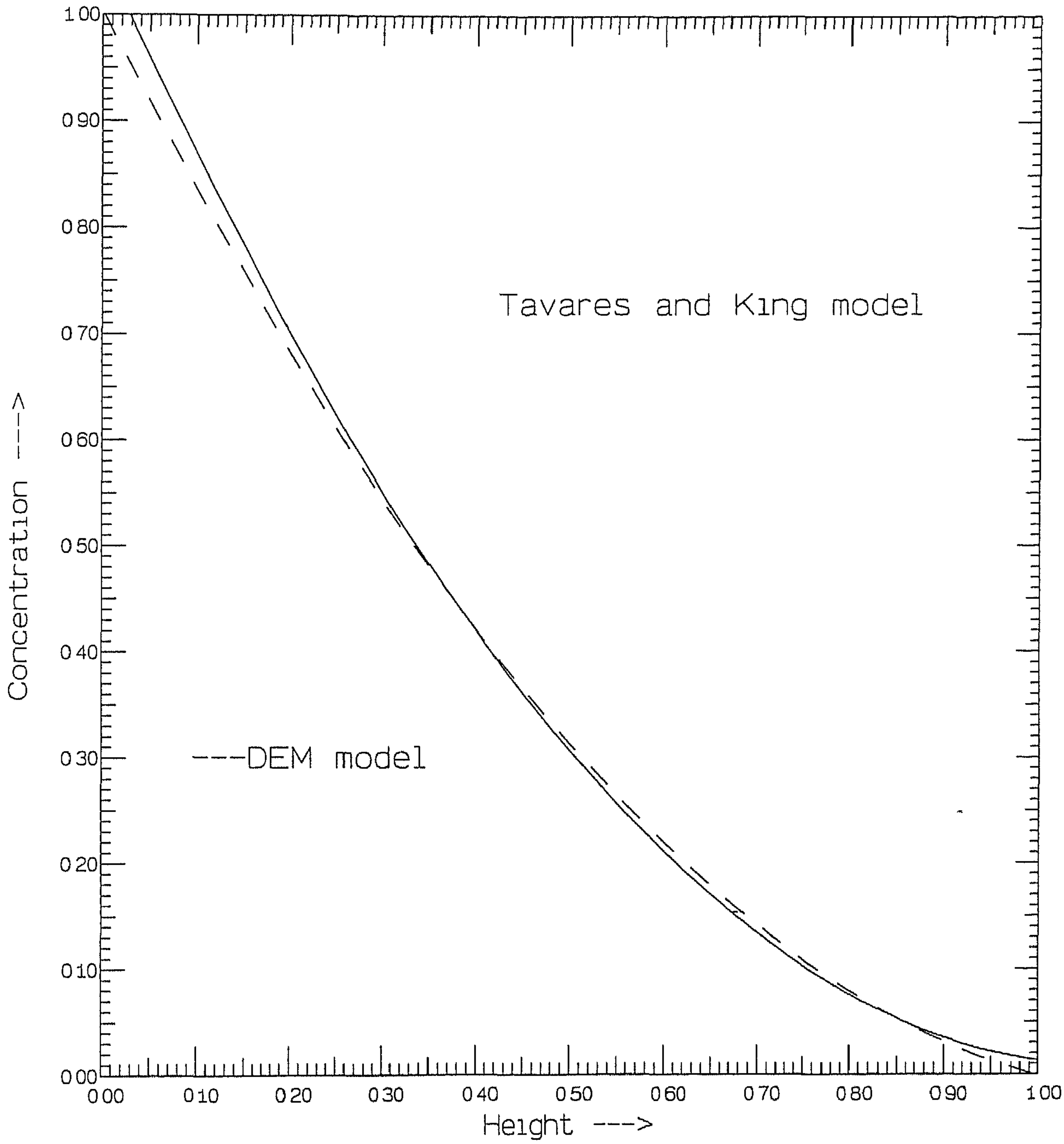

Figure 2 4 Prediction of alpha which suits DEM conc profile

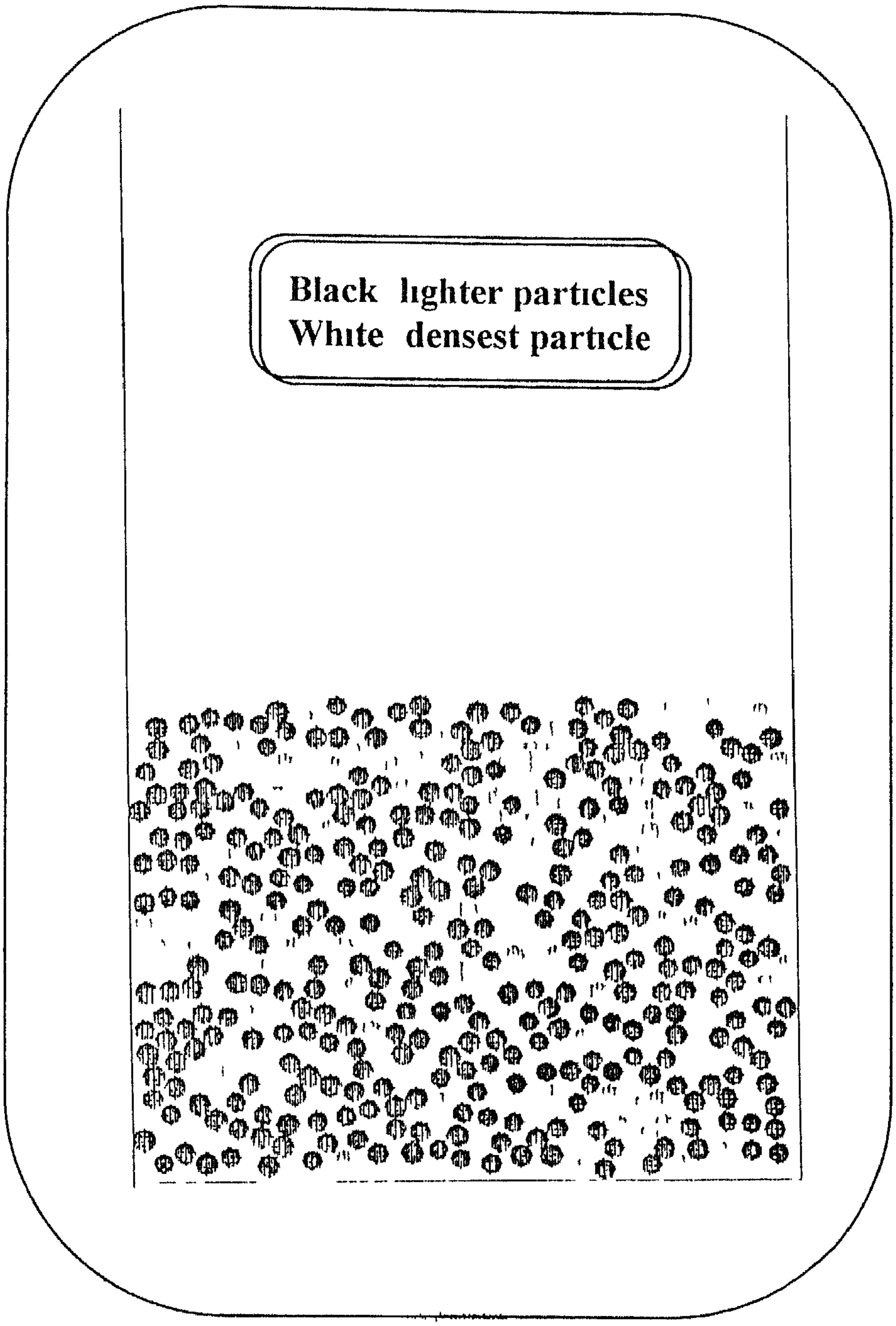

Figure 2 5 Position of particles at the beginning of stratification

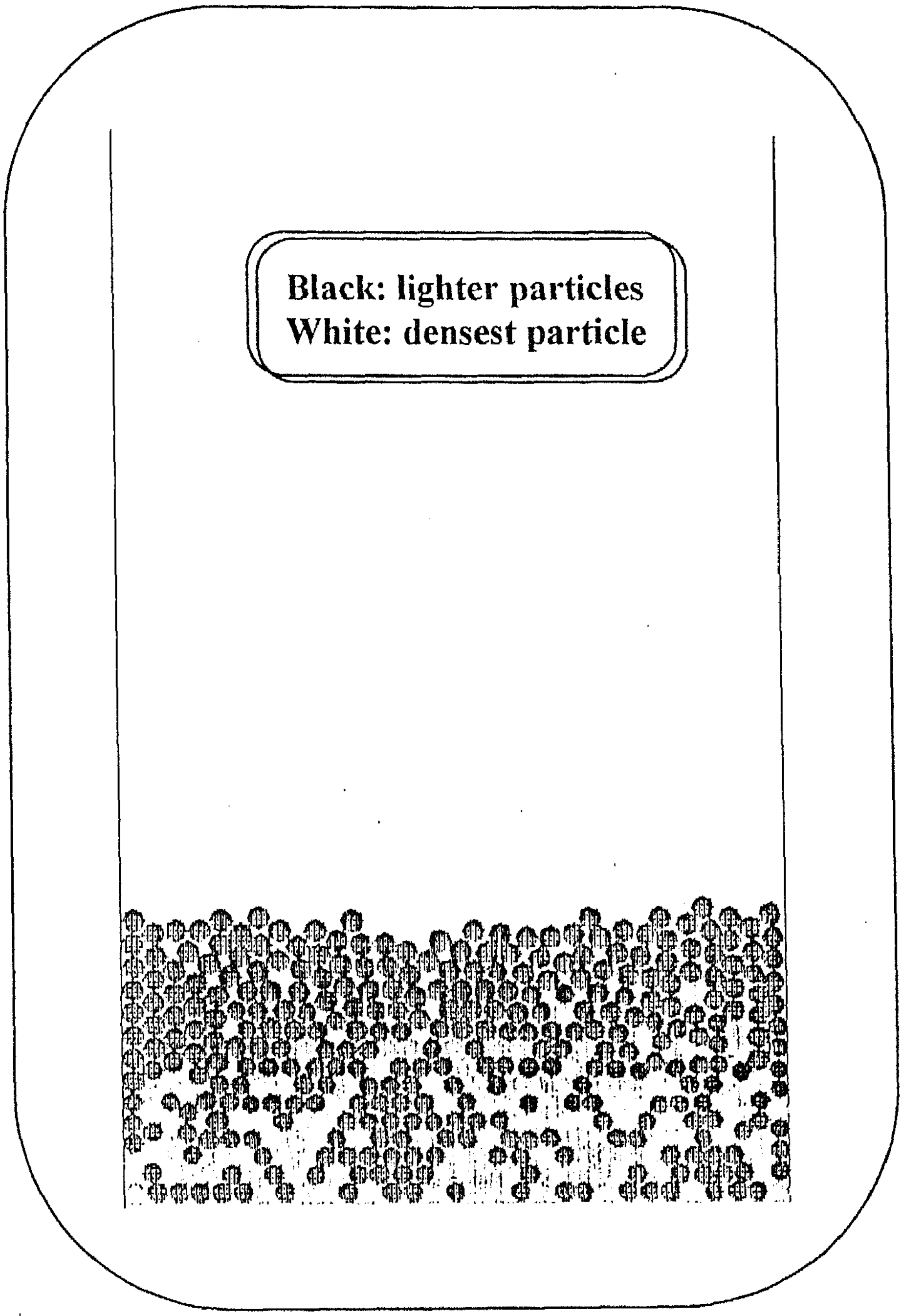

Figure 2.6: Position of particles at the end of stratification

In this chapter study of variation in concentration of different particles varying with respect to size and density is done with the help of DEM model[11] and Tavares and King model[7]

The results of stratification were compared for a single density α value is determined from that comparison Thus if the pulsation rate is known the α value can be predicted by using the DEM model[11] The necessity to have the value of α known apriori is a major draw back of Tavares and King model[7] Further till date Tavares and King model[7] is applicable for monosize particles But in practice analysis has to be done with particles differing not only in density but also in size In these respects DEM model proves to be a better model that can be used to study stratification in jig

Chapter 3

FUZZY LOGIC CONTROL

Application of control theory in mineral industries is increasingly gaining importance primarily to decrease the cost of production and sustain competition in terms of quality Having said that, there is no denying the fact that the unit operations involved in processing minerals are quite complex requiring careful system analysis prior to process control The unit processes typically are characterised by nonlinear relationships between input and output variables Many of these variables cannot be monitored accurately on- stream Therefore, long time lags on the measurement loops are common features of these systems The processes, themselves, often have long time varying responses while the process loads fluctuate significantly on a short term basis Attempts to control these processes have led to the formulation of mathematical models to describe each unit process Adaptive techniques have also been tried to compensate and account for process changes and vageries Some of these approaches are mathematically rigorous so much so that their use has been found limited

In order to control nonlinear and complex processes, a different theory known as *Fuzzy Logic Control* which is completely different from the classical control theory is considered The reason for choosing Fuzzy logic control as a control strategy lies in the complexity of the process being analysed Complex industrial processes[13,21,22 23] like blast furnaces, cement klins, and basic oxygen steel making are very difficult to control This difficulty is due to the complex nonlinear and time varying behavior of the process, that cannot be

predicted accurately Hence in such cases the quality and quantity of the product produced was in the past left in the hands of human operator This resulted in poor quality of the product produced However, in many cases it has been shown that with the use of fuzzy logic control, the process performance is improved significantly

The basic idea of fuzzy logic control is to control such complex processes by studying the behavior of the human operator who controls the process by his experience Analysing the intuitive approach of the operator, several rules called fuzzy rules are framed to tackle the process The uncertainty and imprecision that is encountered in the analysis of the process through the intuitive approach of the operator is easily quantified by fuzzy set theory

Historically, probability theory has been the primary tool for representing uncertainty in mathematical models Its continual use has led to the belief that all uncertainty found within a process must follow random uncertainty A random process is one where the outcomes of any particular process are strictly a matter of chance However, not all uncertainty associated with a process is random, some forms of uncertainty are nonrandom and hence cannot be modelled by probability theory Fuzzy set theory[16,18] is a powerful tool for modeling the kind of uncertainty associated with vagueness, impression, and/or with a lack of information regarding a particular element of the problem at hand

What is fuzzy set theory?

Fuzzy set theory is a term that is applied to fuzzy sets Fuzzy set[13,15] in turn, may be viewed as a mathematical construct to quantify uncertainty arising from defination of an event rather than its occurance or nonoccurance Consider the following problem A room contains 100 people Each of them are coming out of the room one at a time The height distribution of the people in the room is given in figure 3 1

The following questions are posed

(a) What is the probability that a person over the height of 6 feet will come out?

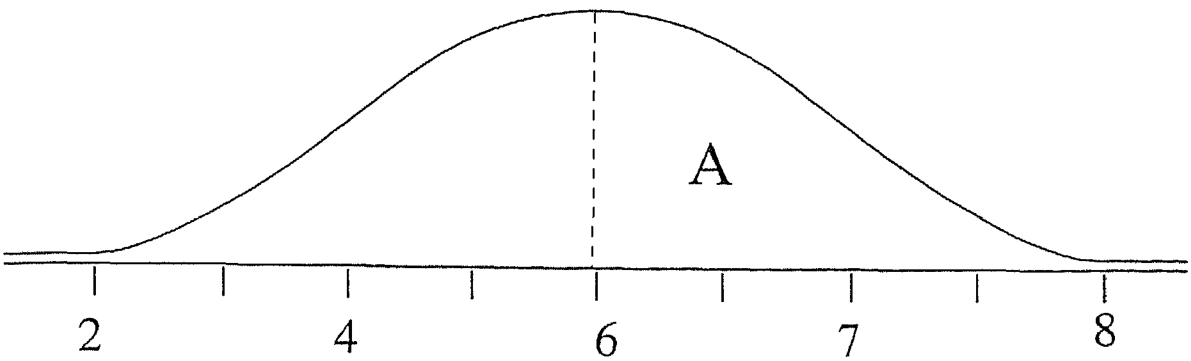

Figure 3 1 Normal distribution of height of people in a room

(b) What is the probability that a *tall* person will come out?

The answer to question (a) is simple and is given by the area 'A' However, the answer to the second question is not easy The reason is that we are not sure as to what is meant by *tall* In other words, we are not sure whether to place the person in the set of *tall* people or not This type of uncertainty araises due to ambiguity present in the defination of *tall*

The idea of fuzzy set theory is to quantify such uncertainty through graded membership in a set If we were to define a crisp set[15] called *tall* we would have to decide on a cut off as shown in figure 3 2

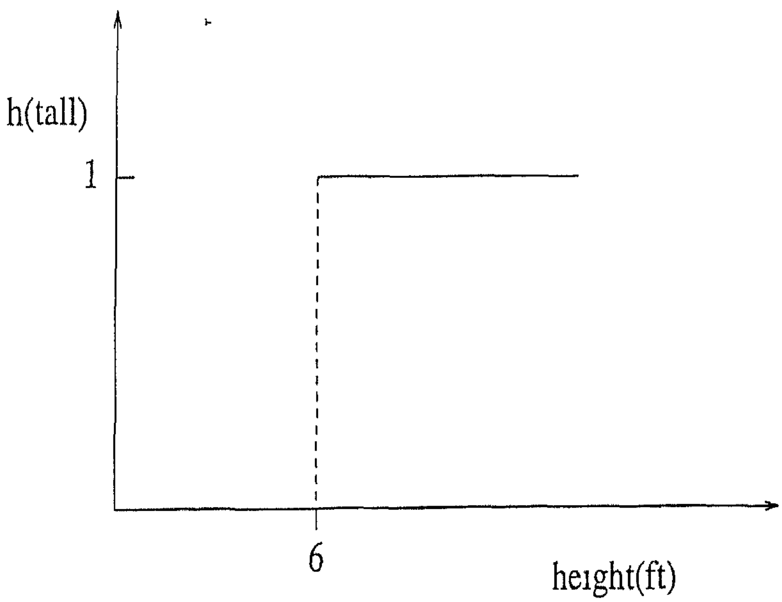

Figure 3 2 A crisp set

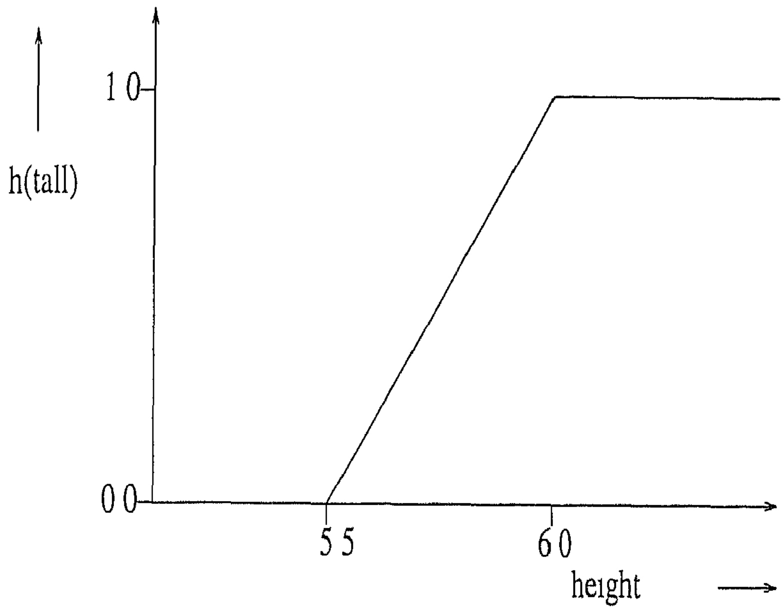

Figure 3 3 Fuzzy quantification of set *tall*

This set defination says that a person with height 5 9 is not *tall*, however a person with 6 1 is *tall* Considerable argument may araise due to the fact that we as humans are not used to such strict cutoffs and feel that such quantification introduces adhoc judgements A better and more realistic way would be to grade the membership in the set *tall* For example, figure 3 3 states that although somebody below 5 5 definitely not *tall* and somebody above 6 0 is definitely *tall*, some doubt exists about the persons with height between 5 5 and 6 0 It furthur states that people with height closer to 6 0 definitely belong more to the group *tall*, than those whose height is closer to 5 5 Such gradation in membership allows for a much closer approximation of the notion present in the word *tall* and such sets are called fuzzy sets In the following, the idea of fuzzy sets and some definitions with regard to fuzzy set operations is presented

3.1 Fuzzy Set

A set is a group of elements which share a common feature For example, a set of numbers greater than 5 contain as its elements, numbers which share the common feature of being larger than the number 5 Sets are defined on an Universe through a mapping say

ff that maps every element $x \in X$ to either a zero or a one, or to any real number in the interval [0,1] A crisp set is defined by its characteristic function and a fuzzy set is defined by its membership function as described below

- If C is a crisp set defined on the universe X, then C is defined by the characteristic function $h_c \quad x \mapsto [0,1]$ Here h_c assigns to each element $x \in X$ a number 1 or a number 0 depending on whether x belongs to C or not

- If F is a fuzzy set, defined on the universe X, then F is defined by its membership function $\mu_F \quad x \mapsto [1,0]$ Similarly, μ_F assigns to each element $x \in X$ a number between 1 and 0 depending on the degree to which the element x belongs to F

Having developed a knowledge of fuzzy sets, it then remains to build the set by means of membership functions There are different membership functions which are used to assign membership values of a fuzzy set If A is a fuzzy set whose value is divided into three classes, say small, medium, large, then the membership functions for these classes can be represented in number of ways depending on the situation Some of the membership functions used are shown in the figure 3 4

Finally, different operations that can be applied to fuzzy sets are similar to classical set theory operations such as union, intersection, and complement Fuzzy sets follow certain properties as an ordinary set Some of the properties[13] which they follow are commutativity, associativity, distributivity, idempotency, transtivity, and identity A detailed discussion on fuzzy set theory is available in the pioneering article by Zadeh [16,17,18]

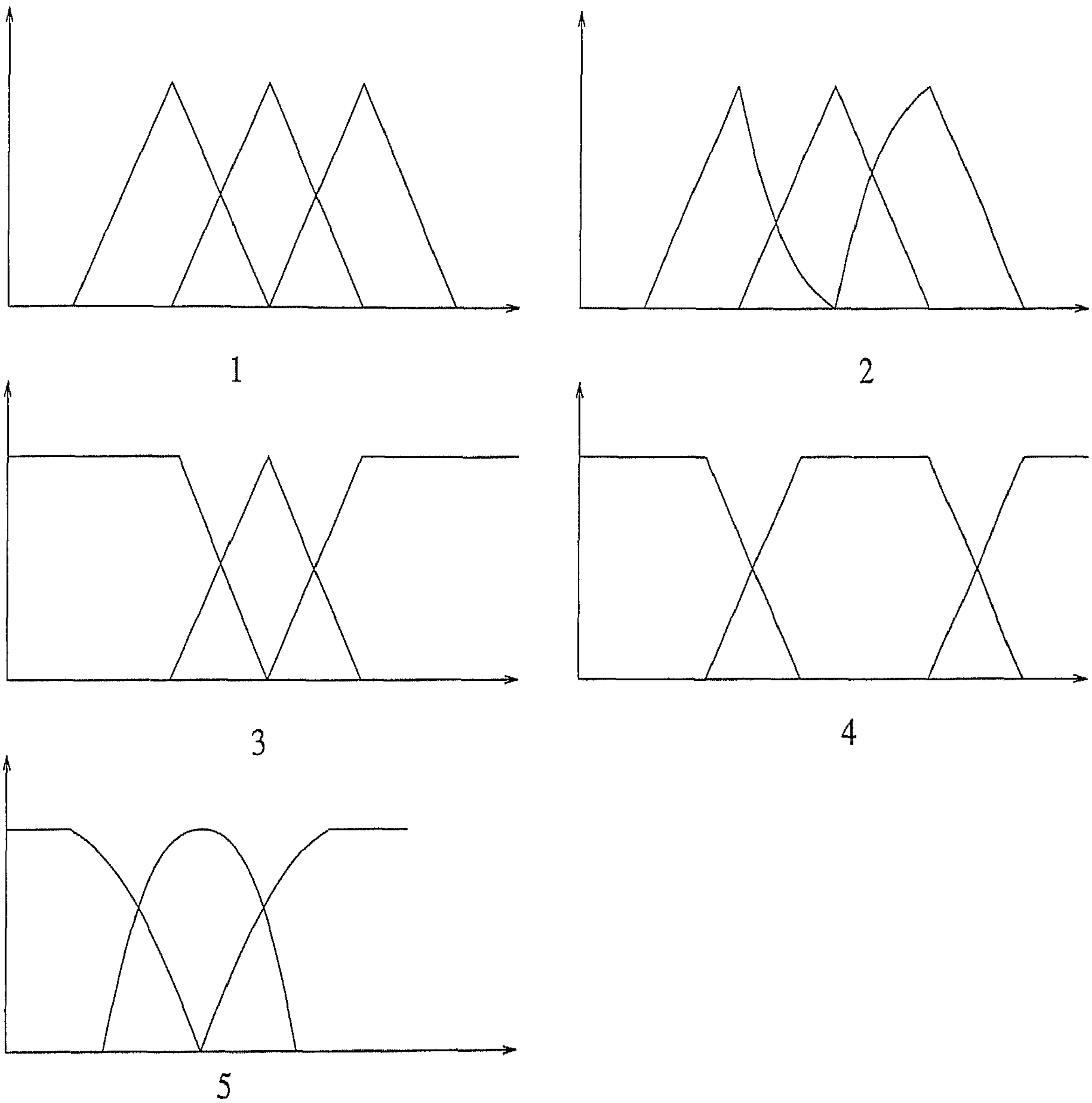

Figure 3 4 Different membership functions

3 2 Design of a Fuzzy Logic Controller(FLC)[15]

The essentıal requırement of any controller, more so ın fuzzy logıc control, ıs a thorough understandıng of the process beıng controlled One should understand whıch varıables aıe key components of the process, how does dıfferent varıables ınteract, and manıpulatıon of whıch varıables ıs the most effıcıent ın modulatıng the process Gıven these prerequıstes, ıt ıs not a dıfficult task to desıgn a fuzzy logıc controller

3 2 1 Steps ın Fuzzy Logıc Control[15,20]

The essentıal components of anv fuzzy logıc control are

1 Determınatıon of the states (or aspects) of the process to be observed and used as ınputs Determınatıon of whıch control actıons are to be consıdered

2 Determınatıon of fuzzy sets definıng the parameters of each of the observed varıables

3 Desıgnıng of the rule base

4 Desıgnıng of the computatıon unıt

5 Determıne an adequate defuzzficatıon unıt (ıf necessary)

A block dıagram of a tı pıcal fuzzy logıc controller[15] ıs shown ın figure 3 5

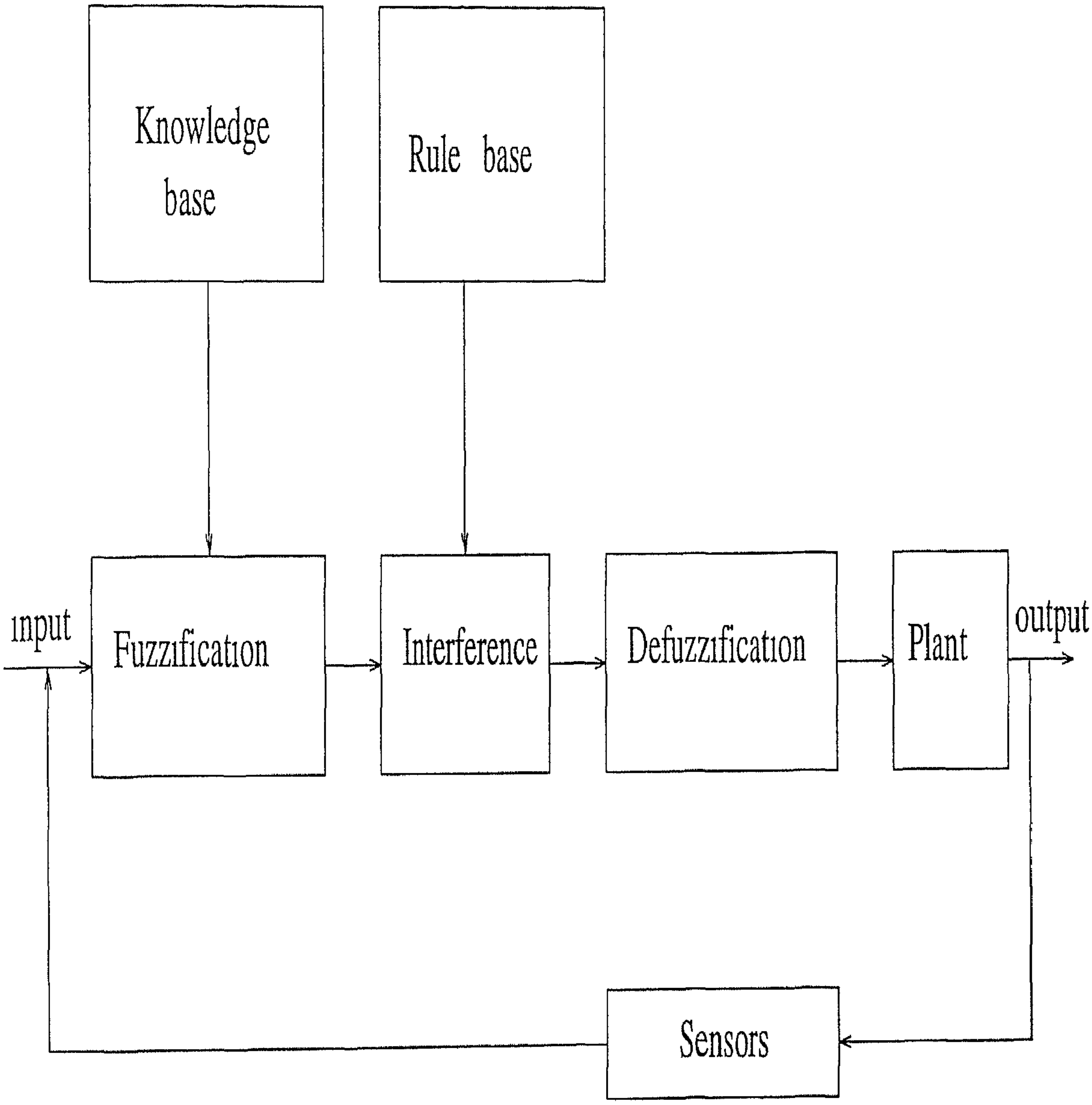

Fıgure 3 5 Block dıagram of FLC

3.3 Application of Fuzzy Logic Control to Jigging

The idea of jigging is to separate different types of particles from a mixture based on their density The controller, therefore, shall measure the extent of separation and suggest adequate action The separation of particles of different size and density, is recognised based on the center of gravity difference, as *cgdiff*, between individual assembly of particles Thus, difference in the center of gravity between two types of particles differing in density is used as a measure of separation When the particles are randomly mixed, the *cgdiff* is more or less zero and when they are agitated the *cgdiff* will take a fixed value depending on the spatial position of particles However, the particles are often in an agitated state during the jigging process and thus the value of *cgdiff* by itself will not adequately describe the extent of separation In order to overcome this drawback the jigging time, as *time*, is also taken as one of the state variables

Stratification of particles in jig is achieved by pulsating the jig bed by means of a moving fluid The fluid velocity[14,19] is given by

$$v(t) = a\omega \cos(\omega t) \tag{3 1}$$

where a is the amplitude in metres and ω is the frequency in cycles/seconds Hence, amplitude and frequency of pulsation are two important parameters which can be manipulated to obtain the desired separation

In summary, the state variables for the jigging process is identified as **cgdiff** and **time** The control variables are identified as *amplitude* and *frequency* of pulsation It is believed that a host of other factors such as feed grade, bed height, etc , play an important role in the stratification process However, these factors are not dealt in this thesis

The jigging process is analysed with the help of a simulator based on DEM model that replaces the jig equipment Numerical simulations are done to study the jigging behavior of 435 particles of two different densities The effect of amplitude and frequency of pulsation

is studied by means of *cgdiff* analysis This is nothing but to determine the difference in the center of gravity of the two assemblies of particles as jigging progresses The results were analysed and variation of cgdiff with time were studied The state variables *cgdiff* and *time* were then classified into different classes based on the results of simulation Here the variables *cgdiff* & *time* are divided into three linguistic classes as small, medium, and large and accordingly the membership functions of the variables, of these classes are shown in figure 3 6 In this figure the x_coordinate is dependent on the bed height The y_coordinate is the membership value to be assigned

The shape of the membership function chosen is dependent on the complexity of the process Nine rules[14] were formulated based on the different combinations of the variables *cgdiff* and *time* The final actions were calculated using the following relation

$$Newfrequency = \frac{\sum_{i=1}^{n} T_i F_i}{\sum_{i=1}^{n} T_i}, \quad Newamplitude = \frac{\sum_{i=1}^{n} T_i F_i}{\sum_{i=1}^{n} T_i} \tag{3 2}$$

where T_i is the truth value of rule i for a particular input condition The value of T_i is calculated as

$$T_i = min(\mu_j(cgdiff), \mu_k(time)) \tag{3 3}$$

The truth value is taken as minimum of membership values of *cgdiff* & *time* Using these values the new frequency and new amplitude to be applied for next cycle is found Thus the cycle is carried out and once the required *cgdiff* is obtained the fuzzy rules stop working In a continous process it would just decrease the amplitude and frequency to such lower levels that further stratification shall not be allowed

A computer program is developed for applying the rules of fuzzy logic control This program is incorporated to the main DEM program as a subroutine A flow sheet explaining the fuzzy logic portion of the computer program is presented in figure 3 7

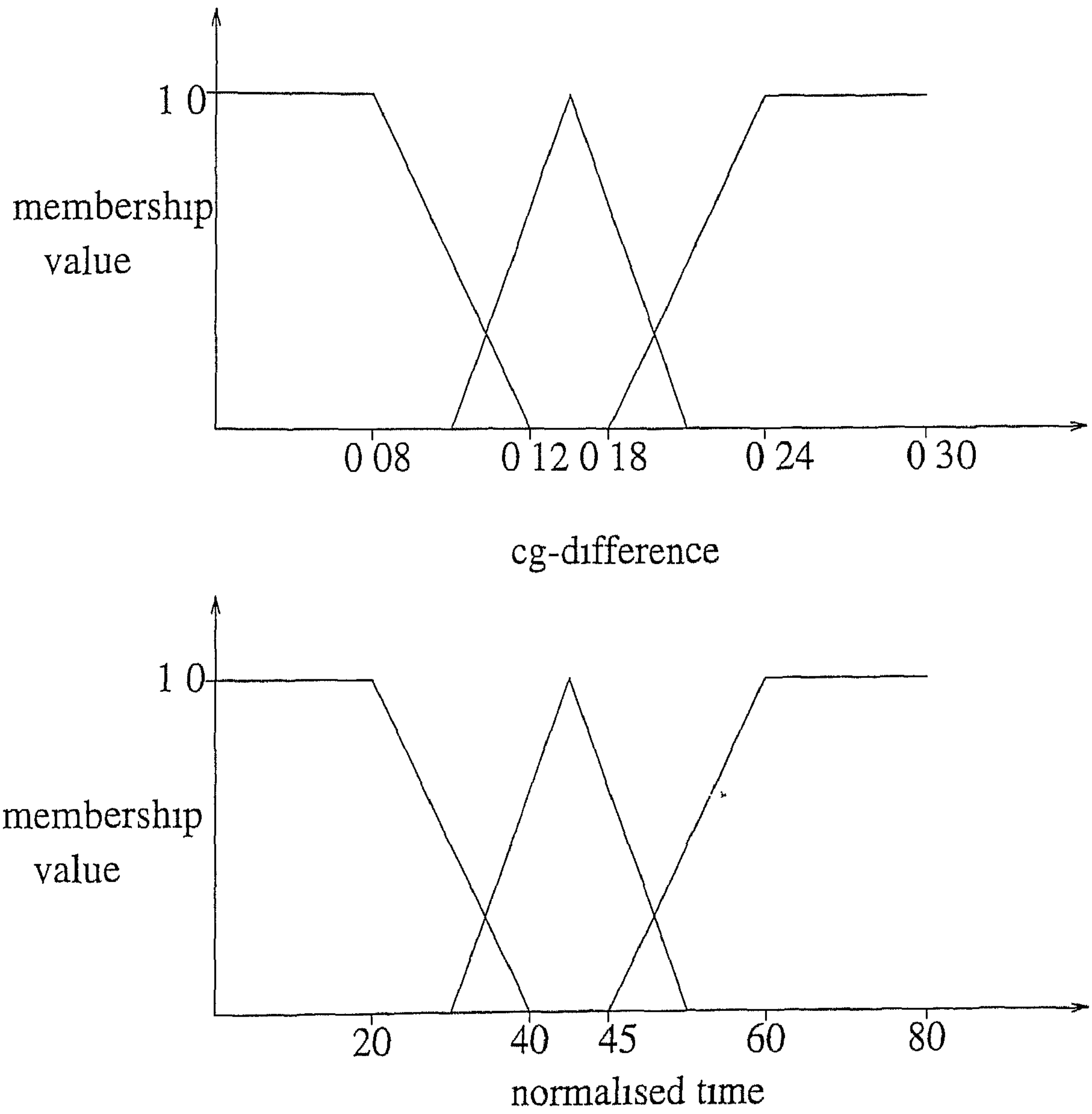

Figure 3 6 Membership functions defining *cgdiff* and *time*

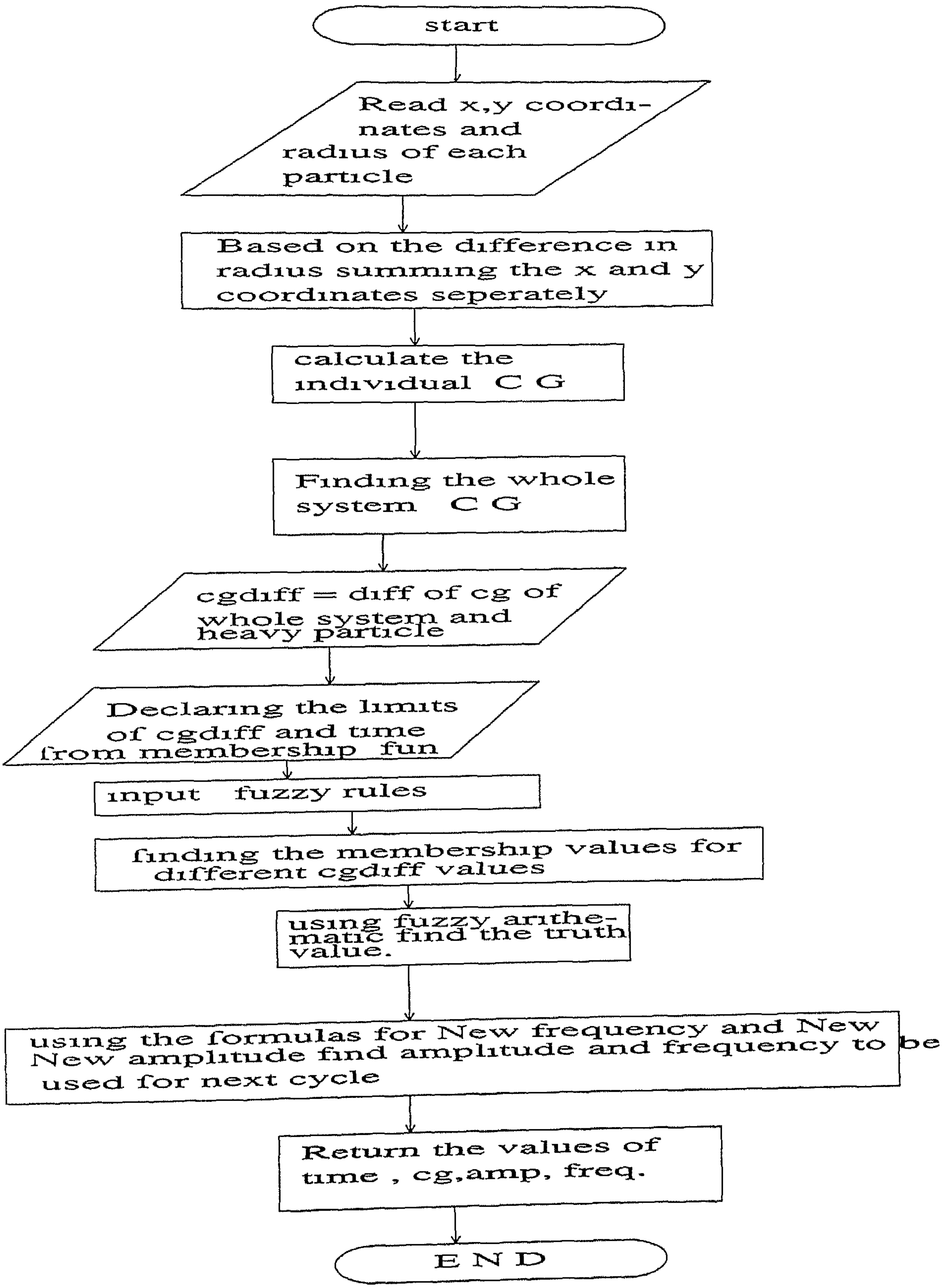

Figure 3 7 Flow sheet of fuzzy logic control application

Chapter 4

NUMERICAL SIMULATION

In order to analyse the nonlinearity and complex nature of stratification of particles taking place in a jig a simulator is used This simulator uses the discrete element method (DEM) to calculate the interaction and motion of particles This code has been tested to work satisfactorily for other mineral processing units involving discrete particles [11] It is used in the present case to analyse the variation in the center of gravity of different particle groups (differing in density) during jigging This variation is brought about by changing the amplitude and frequency of the pulsation cycle during jigging Experienced gained through extensive simulation allowed the fuzzy rules to be framed These rules are incorporated in a separate computer program that acts as a subroutine to the main DEM code At the end this new computer code is used to study the performance of the controller

4.1 Process Analysis

Several simulations were carried out to study the system behavior as this is the crucial step in building the fuzzy logic controller In each of these simulations only two types of particles were used These particle properties are shown in Table 4 1 A total of 435 particles were used A jig bed of 2- × 3-m is used to contain 435 particles Simulations were carried out for sufficient number of cycles such that all the features corresponding to the stratification process are revealed For example, a total time of 30 seconds is allowed

Table 4.1 Specifications of particles used in the simulation

Sl no	1	2
Size(radius in m)	0.034	0.036
density(kg/m^3)	2500	1500
No of particles	218	217

for stratification in all but one case. Altogether, 25 numerical simulations were carried out. Other pertinent data with regard to these simulations is given in Table 4.2. All simulations performed as mentioned in Table 4.2 is also analysed by studying the variation in *cgdiff* versus *time*. Here *cgdiff*, is the difference in the center of gravity of the heavy particle type and the whole system. Similarly, *time* is the normalized time obtained as follows. The time step for simulation is taken as 0.22e-03 second and the total time of simulation is 30 sec. The positions of the particles inside the jig is analysed after every 1000 timesteps. Hence, normalized time is $0.22e-03 \times 1000/0.22$. This way, each sequential snapshot that is taken for analysis after 0.22 seconds differ by one in normalized time scale. In order to assess the progress of the simulation, it is desired that the theoretical maximum of the degree of stratification be known for a given system. In the present case it is quantified by computing the theoretical *cgdiff*. For the 435 particle system this *cgdiff* is determined as 0.3-m. All the simulation results are compared with this number to ascertain the degree of stratification. A schematic representation of a completely stratified bed is shown in figure 4.1

Table 4 2 Lıst of numerıcal sımulatıon performed for process analysıs

Amplıtude	Frequency	Peak cgdıff	Statıc cgdıff	Energy loss
0 1	8	0 0736	0 0376	2636 872
0 1	11	0 1402	0 1366	7743 352
0 1	14	0 2492	0 2114	10444 43
0 1	17	0 2204	0 197	12084 01
0 1	20	0 1708	0 1204	13680 76
0 1	24	0 1352	0 1132	18669 76
0 11	8	0 1092	0 0745	3085 369
0 11	11	0 1695	0 1485	8739 529
0 11	14	0 2708	0 205	11222 07
0 11	17	0 1903	0 1717	13217 69
0 11	20	0 205	0 1411	15029 17
0 11	24	0 1752	0 1606	16217 80
0 12	8	0 1428	0 1019	3801 153
0 12	11	0 2179	0 1789	9812 657
0 12	14	0 2715	0 1867	11778 20
0 12	17	0 2179	0 1769	14276 88
0 12	20	0 1682	0 1448	16291 65
0 12	24	0 1584	0 1214	19383 40
0 13	8	0 1321	0 1074	4312 438
0 13	11	0 2043	0 1644	9094 957
0 13	14	0 2725	0 2005	11880 58
0 13	17	0 2186	0 1492	15395 30
0 13	20	0 191	0 1663	17346 87
0 13	24	0 1587	0 134	20995 80
0 14	8	0 1686	0 1474	5105 190
0 14	11	0 2064	0 2023	11724 19
0 14	14	0 2935	0 2109	14271 92
0 14	17	0 2085	0 1646	15989 62
0 14	20	0 1896	0 152	18085 36
0 14	24	0 156	0 1259	22453 42

Results of simulation is presented in a series of figures from 4 2 to 4 6 These figures show the variation in the *cgdiff* with *time* for different levels of amplitudes of pulsation At any given level of amplitude, jigging is done at different levels of frequency In other words, the jigging cycle was made to vary It is seen from these figures that the *cgdiff* starts increasing with time for any amplitude and frequency and then reaches a peak value Further increase in jigging cycle decreases the *cgdiff* The initial increase in *cgdiff* is due to the readjustment of particles in such a way that the heavier particles have a tendency to move downwards and vice-versa However, as jigging is allowed to progress beyond this point the already stratified bed do not get disturbed any longer because the particles have already swapped places The dilation of the bed is reduced, thus, there is a decrease in *cgdiff* It is not only the extent of pulsation but the frequency of pulsation also affect the degree of stratification It is observed that at any given amplitude, the peak value of *cgdiff* increases with frequency up to a certain value and then decreases with increase in frequency The effect of amplitude is also same as that of frequency It is unclear as to which one has the maximum effect on degree of stratification The effect of frequency on *cgdiff* at constant amplitude, and that of amplitude at constant frequency are shown in figure 4 7 and 4 8 However, the combined effect of frequency and amplitude is best illustrated by means of a 3d-plot as shown in figure 4 9 These figures show that the best stratification is obtained for a fixed value of amplitude and frequency This is the operating point at which the *cgdiff* is maximum

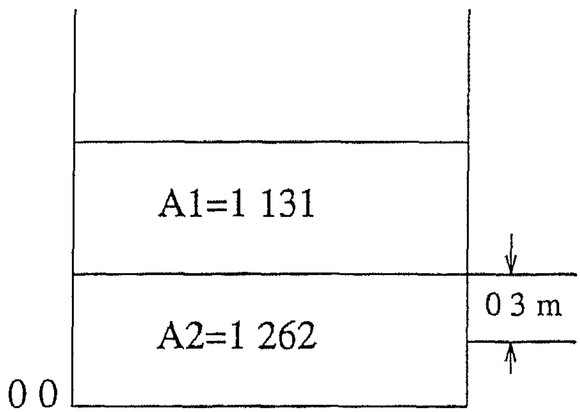

Figure 4 1 Complete separation of two types of particles

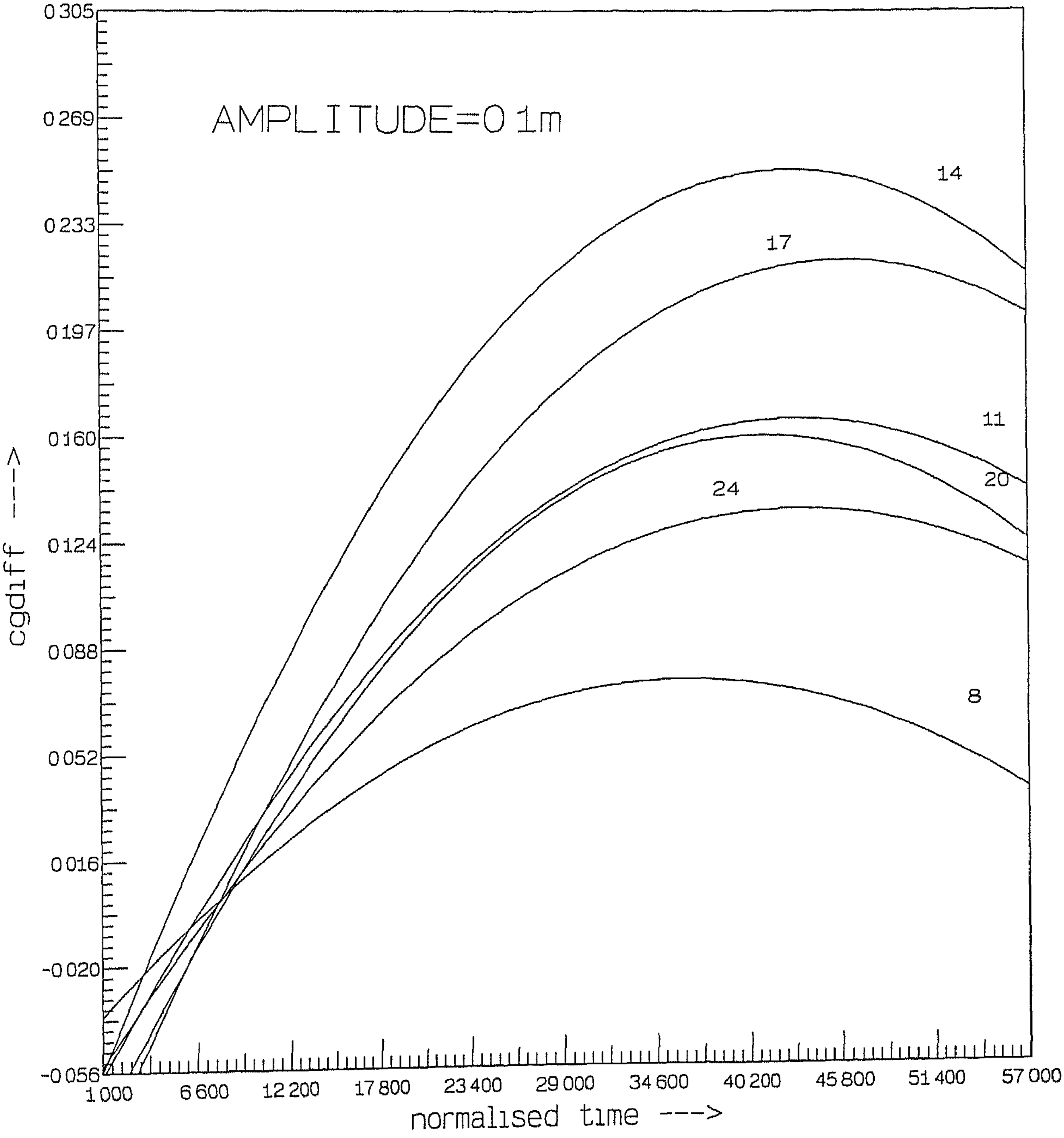

Figure 4 2 Variation of *cgdiff* with *time* for different frequencies

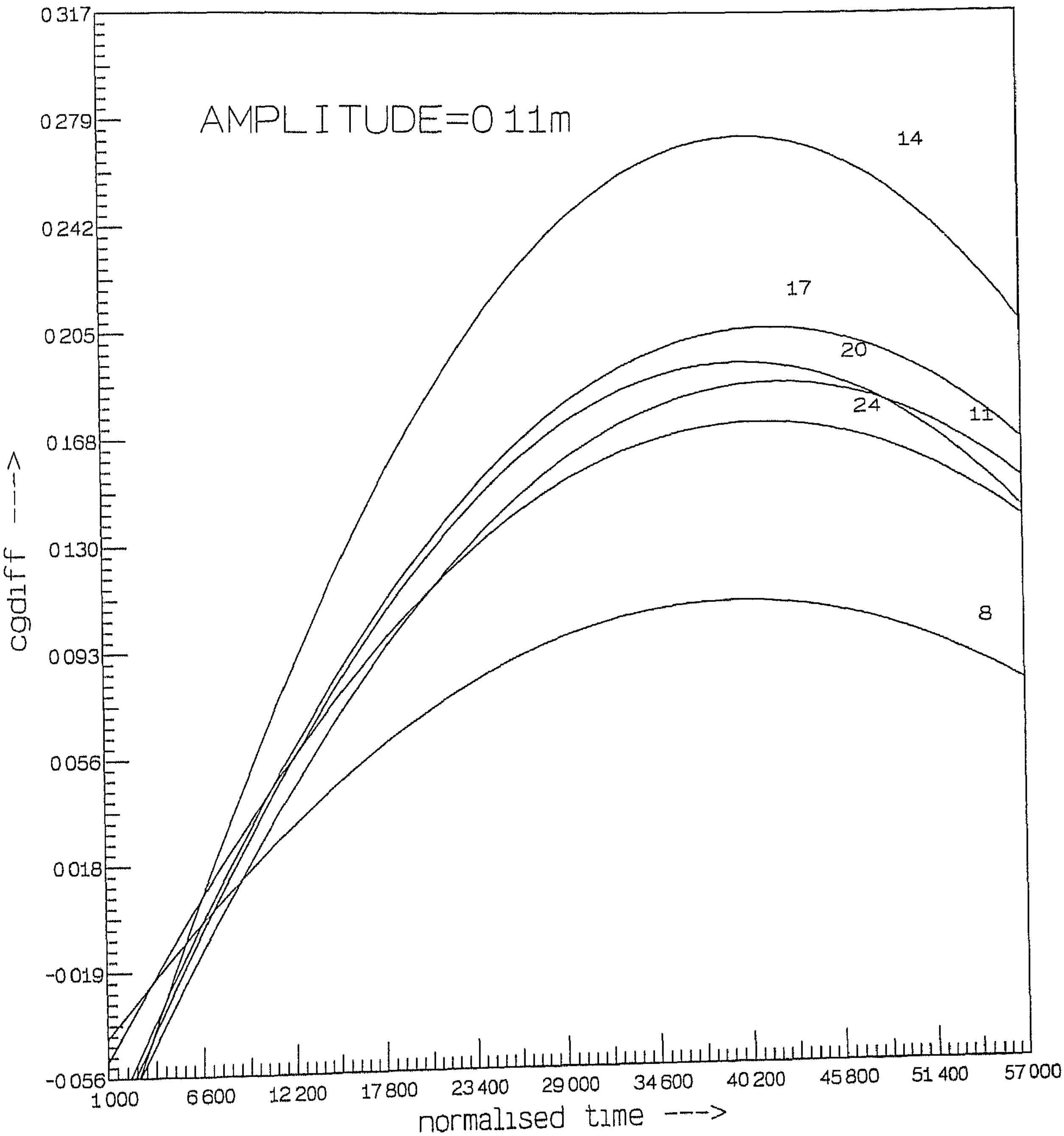

Figure 4 3 Variation of *cgdiff* with *time* for different frequencies

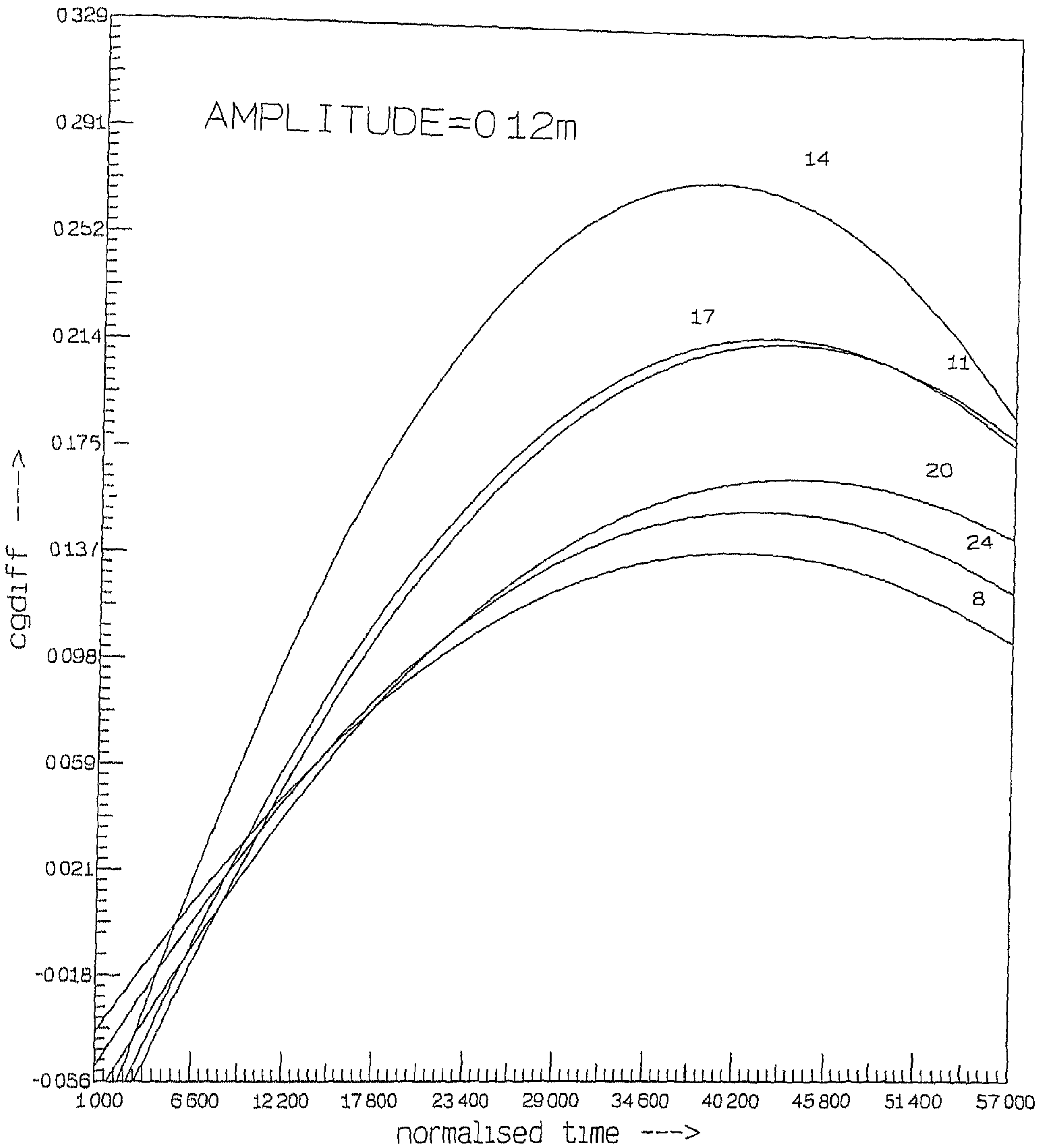

Figure 4 4 Variation of *cgdiff* with *time* for different frequencies

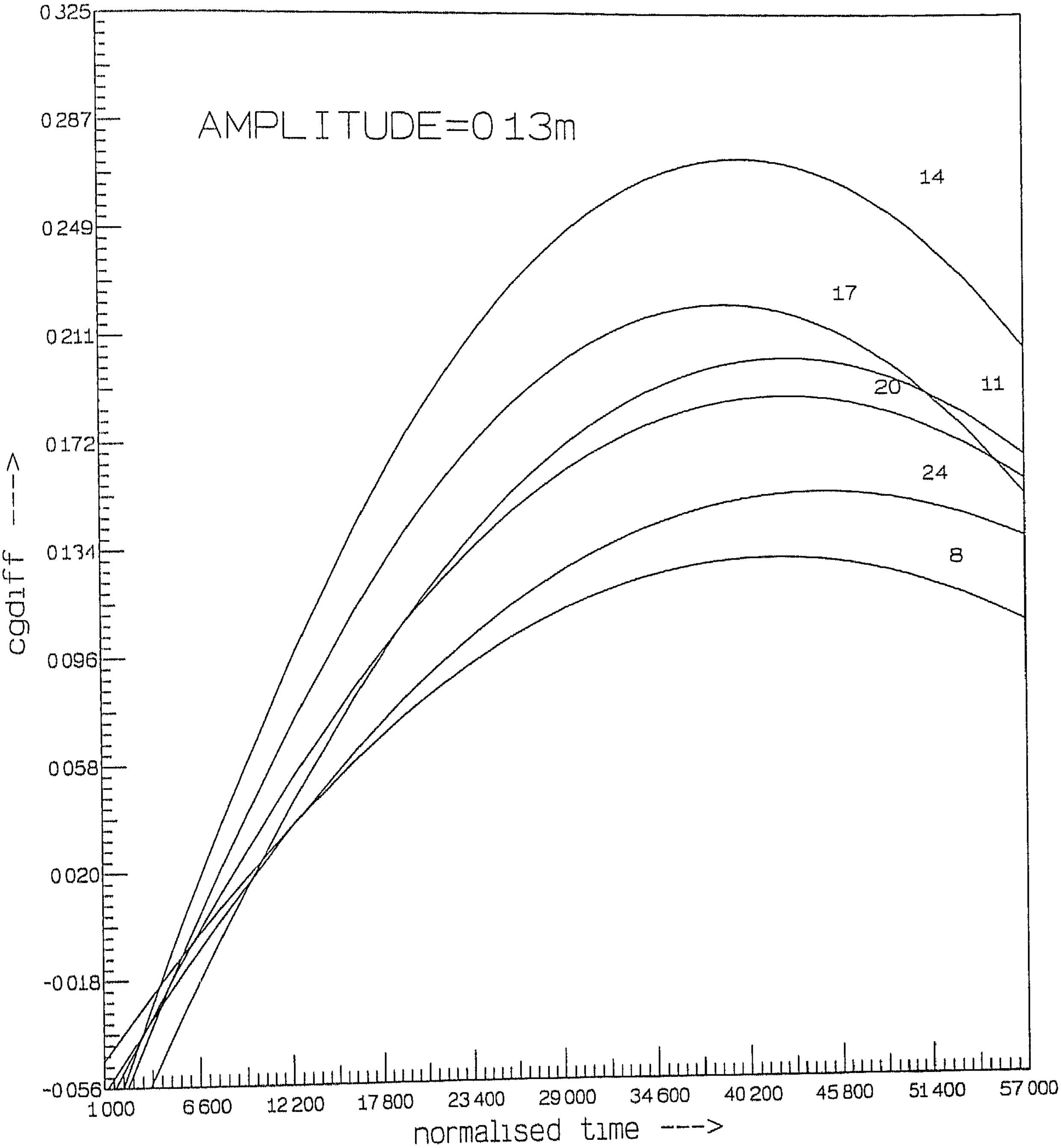

Figure 4 5 Variation of *cgdiff* with *time* for different frequencies

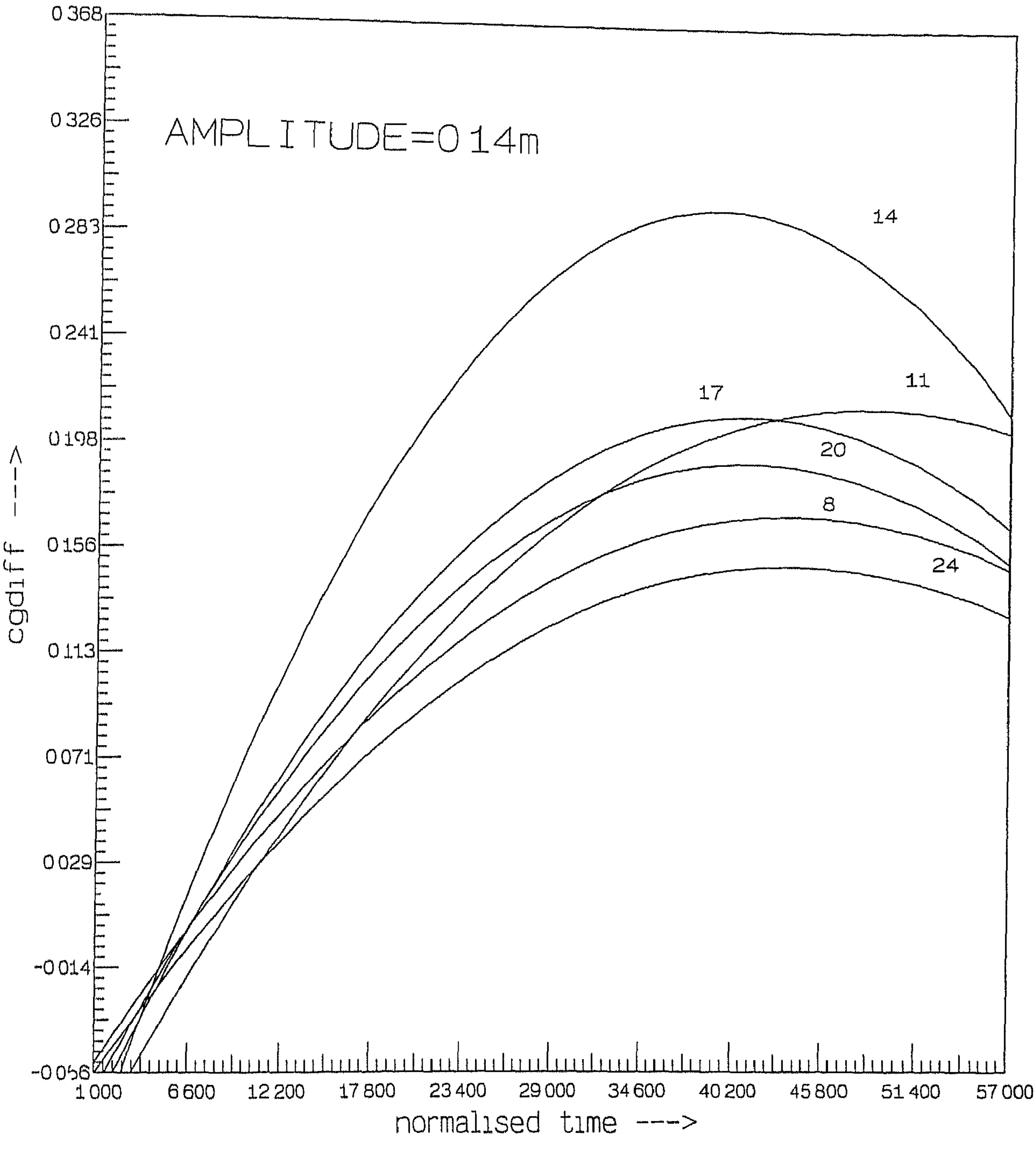

Figure 4 6 Variation of *cgdiff* with *time* for different frequencies

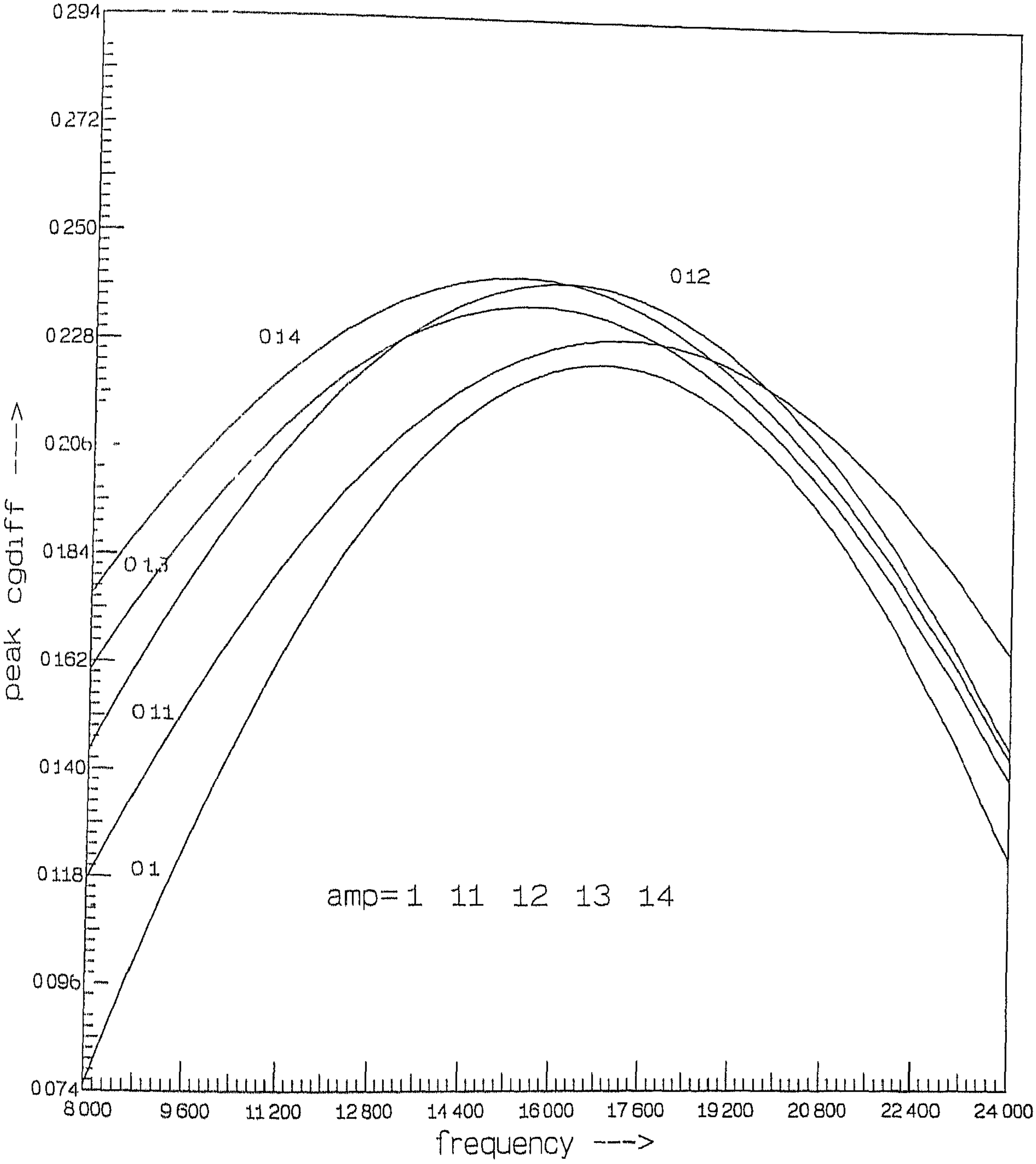

Figure 4 7 Variation of peak cgdiff with frequency

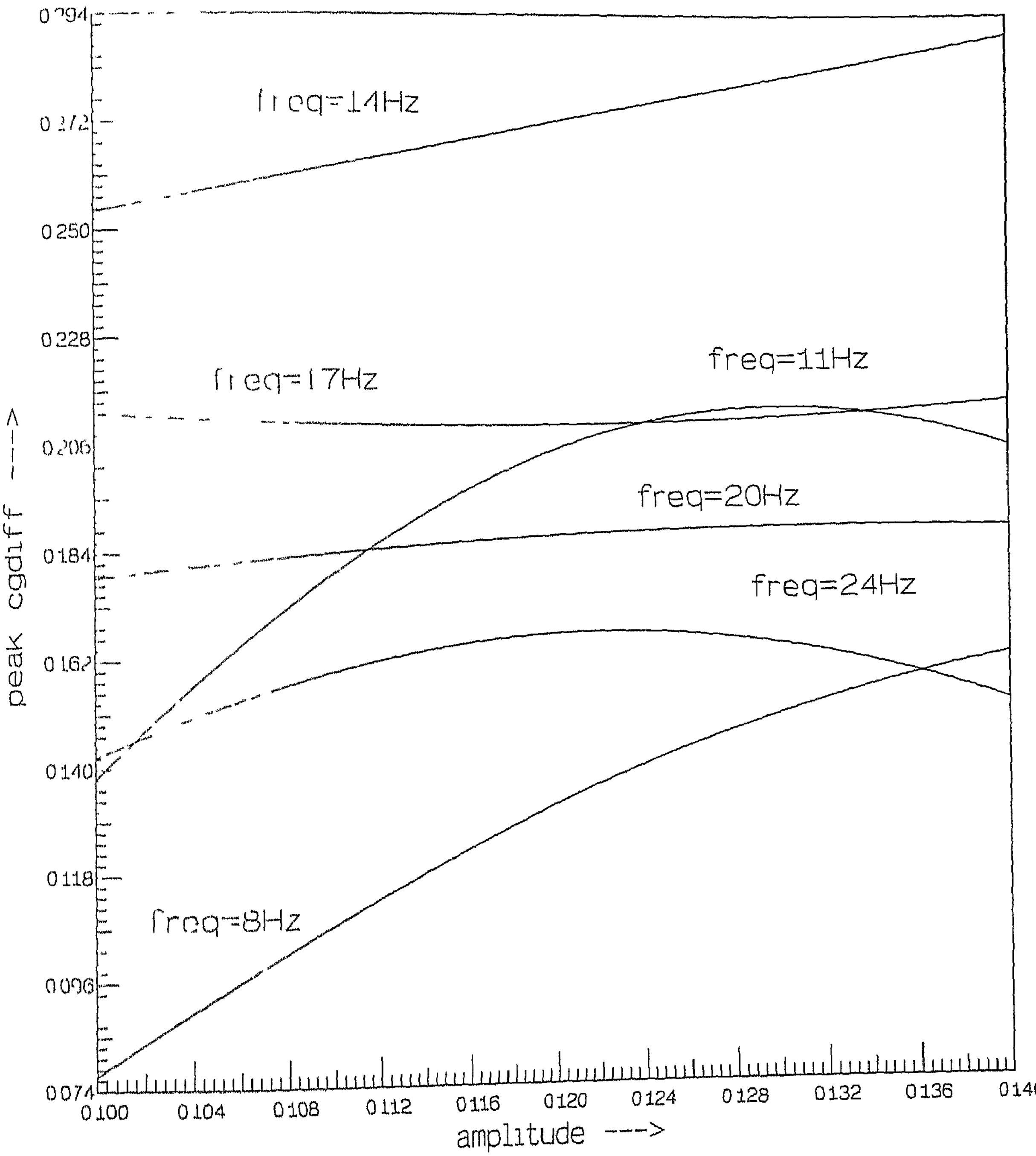

Figure 4 8 Variation of peak cgdiff with amplitude

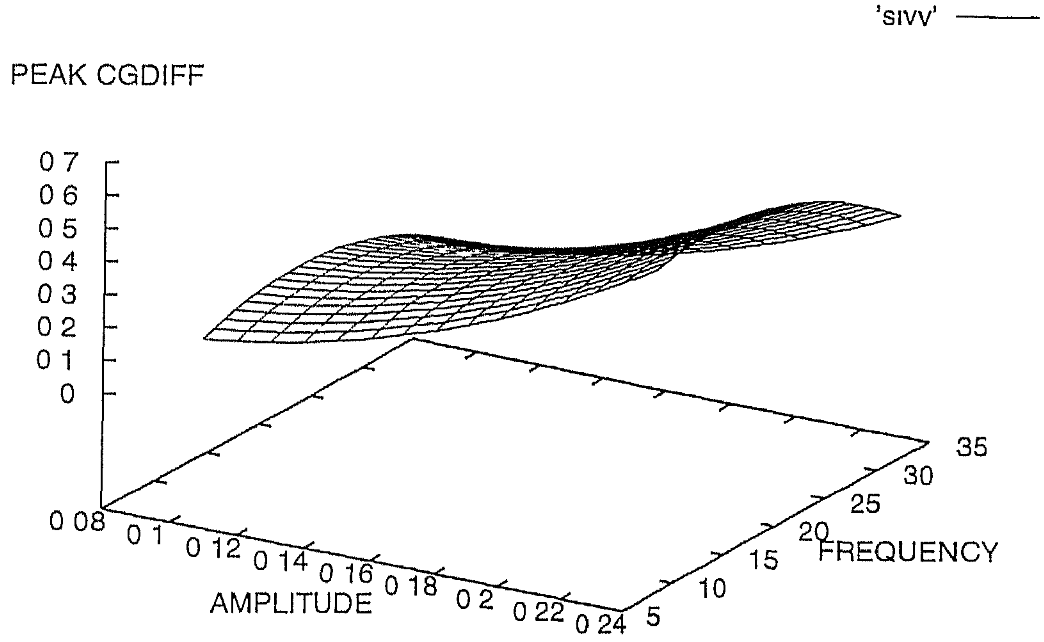

Figure 4 9 Variation of peak cgdiff with amplitude and frequency

The computer code also allows to study the amount of energy spent for a given degree of stratification This data is recorded for all the simulations This data is given in Table 4 2 A graphical representation of this data showing the combined effect of amplitude and frequency on energy spent for jigging is shown in figure 4 10

4 2 Fuzzy Logic Control

The knowledge gained with regard to the process is used for the formation of fuzzy rules (selection of amplitude and frequency) which can be applied for different classes of *cgdiff* and *time* so as to get optimum *cgdiff* and also optimum utilization of energy The fuzzy rules formulated are shown in Table 4 3 Jigging is carried out by applying the fuzzy rules As before, the analysis of the process is done by studying the variation of *cgdiff* with *time* Here this analysis is used to evaluate the performance of the controller A typical result of simulation where the controller is used is presented in figure 4 11 This figure shows that the *cgdiff* increases with *time* up to a certain extent and when the desired degree of stratification is achieved the controller stops the jigging action More importantly, the controller chose to operate the jig in such a manner that the rate stratification is also enhanced

The performance of the controller is assessed by comparing the results of simulation with and without the controller This result is shown in figure 4 12 It is seen here that the controller drives the process at a faster rate and stops after having achieved the desired level of stratification

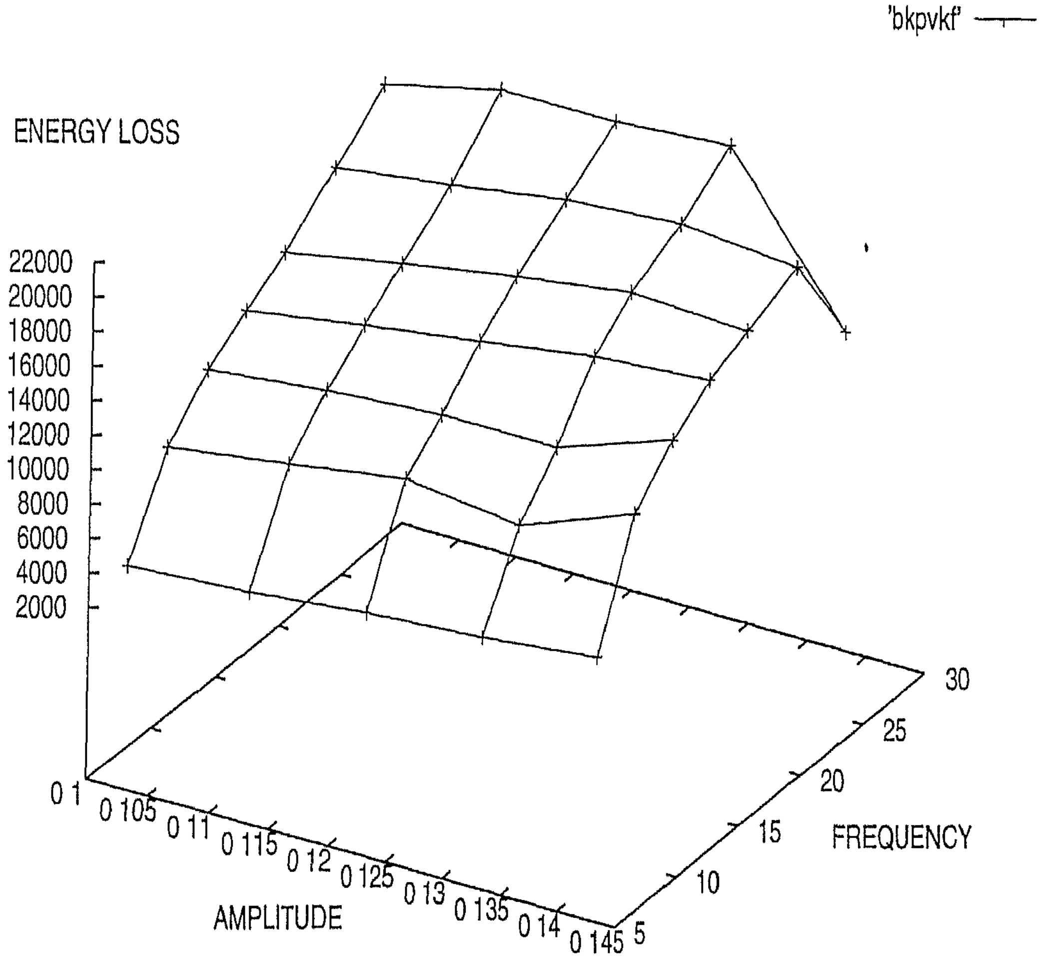

Figure 4 10 Variation of energy loss with amplitude and frequency

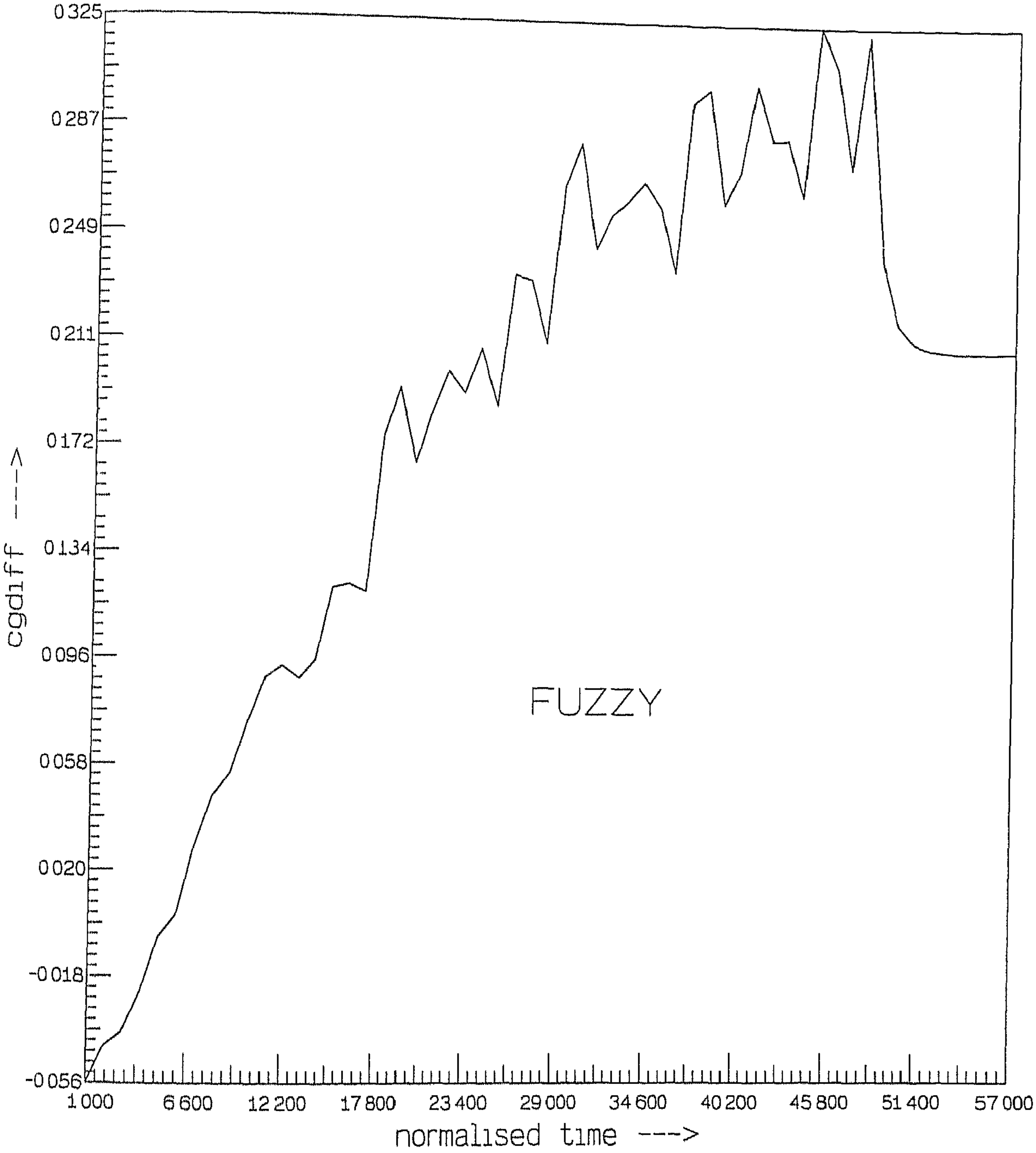

Figure 4 11 Variation of cgdiff with fuzzy application

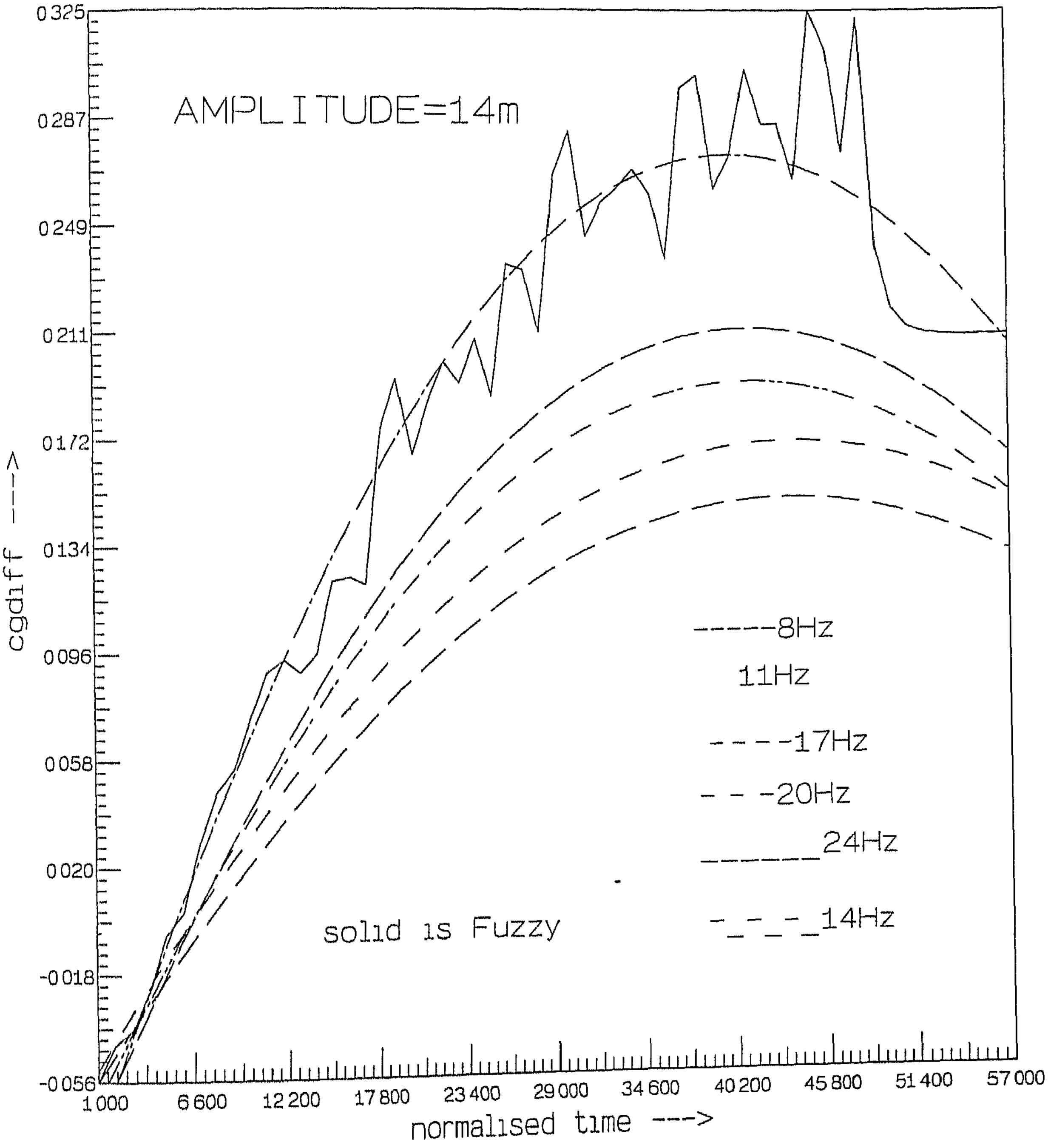

Figure 4 12 Curves showing variation of cgdiff with and without Fuzzy

Table 4.3: Fuzzy logic controller rules

Categories of *cgdiff*	Categories of *time*		
	Small	Medium	Large
Small	$i = 1$ $a_i = 0.14$ $f_i = 14.0$	$i = 2$ $a_i = 0.14$ $f_i = 14.0$	$i = 3$ $a_i = 0.14$ $f_i = 14.0$
Medium	$i = 44$ $a_i = 0.18$ $f_i = 13.0$	$i = 5$ $a_i = 15.0$ $f_i = 17.0$	$i = 6$ $a_i = 0.11$ $f_i = 20.0$
Large	$i = 7$ $a_i = 0.10$ $f_i = 14.0$	$i = 8$ $a_i = 0.11$ $f_i = 17.0$	$i = 9$ $a_i = 0.0$ $f_i = 0.0$

Energy is spent to separate particles by jigging. The energy supplied to the jig is a function of the rate at which the fluid moves in the bed. In other words, it is a function of acceleration of the fluid. Defining a term as forcing factor f, where $f \propto (a\omega^2)$, the amount of energy spent for jigging is estimated for the purpose of comparison. Figure 4.13 shows the variation in the forcing factor with time for two cases: one where the jig is operated in a cyclic manner and the other where the controller is used to decide the amplitude and frequency of pulsation. It is seen here that when the jig is operated in cyclic manner the forcing factor does not change with time. However, when the controller is used the forcing factor, remains unchanged for a certain time and then increases before falling back to the zero level when jigging stops. This increase in the value of forcing factor shows that the energy required for jigging is more than that required without fuzzy logic control. Thus the overall energy requirement with the application of fuzzy logic control is more.

The above result shows that the performance of the controller with the set of rules that are used is not satisfactory. The reason for this poor performance can be explained by means of a typical *cgdiff* vesus frequency plot as shown in figure 4.8. It is seen here that a given value of *cgdiff* can be achieved at two levels of frequencies due to the parabolic

nature of the plot. For example, a *cgdiff* of 0.2 can be achieved at a frequency of 11- and 20-cycles/second. However, if the amplitude of pulsation is fixed, then the energy spent for jigging is higher having used a frequency of pulsation of 20 cycles/sec. Using this idea the earlier fuzzy rules were modified. The new set of fuzzy rules are shown in Table 4.4.

The controller after being tuned is used to control the stratification. The result is presented in figure 4.14 where the variation in the forcing factor with time is shown. The figure shows that change in forcing factor with the application of fuzzy logic control remains again same up to a certain time and falls with time afterwards unlike the previous situation. Thus, the controller is performing better so far as energy consumption is concerned. In fact, by comparing the energy consumption over a period 57 cycles it is found that the use of controller reduces the energy consumption by 20%.

In practice, jigs are operated in a cyclic manner where the pulsation cycle is fixed apriori. It is interesting to compare the pulsation cycle that is the result of the use of controller with a standard one. Figure 4.15 shows such a comparison. The top figure shows the variation in the pulsation in a sinusoidal manner for all times. In contrast to this the bottom figure shows no clear pattern except for the early stages of jigging. This is precisely what is suggested to be implemented in a real situation in order to decrease energy consumption and improve quality of separation.

4.3 Controller Behavior for a Complex System

In all the previous simulation a system comprising of two types of particles is used. But, in reality particles do vary in size and specific gravity. The controller is put to test for more complex system comprising of six types of particles of different size and density. The particle specifications are given in Table 4.5. The density of first three groups of particles is taken the same and so is the case for the other three groups. However, the height of the bed is kept constant as before even though the number of particles increased to 860 in total.

Table 4 4 Modified fuzzy logic controller rules

Categories of *cgdiff*	Categories of *time*		
	Small	Medium	Large
Small	$i = 1$ $a_i = 0\ 14$ f_i=14 0	$i = 2$ $a_i = 0\ 14$ f_i=14 0	$i = 3$ $a_i = 0\ 14$ f_i=14 0
Medium	$i = 44$ $a_i = 0\ 18$ $f_i = 13\ 0$	$i = 5$ $a_i = 15\ 0$ $f_i = 13\ 0$	$i = 6$ $a_i = 0\ 11$ $f_i = 10\ 0$
Large	$i = 7$ $a_i = 0\ 10$ $f_i = 10\ 0$	$i = 8$ $a_i = 0\ 11$ $f_i = 13\ 0$	$i = 9$ $a_i = 0\ 0$ $f_i = 0\ 0$

Table 4 5 Specifications of six types of particles

Sl no	1	2	3	4	5	6
Size(radius in m)	0 034	0 025	0 015	0 035	0 026	0 016
Mass(kg)	0 41159	0 1636	0 0353	0 2692	0 11035	0 0257
No of particles	110	135	185	110	135	185

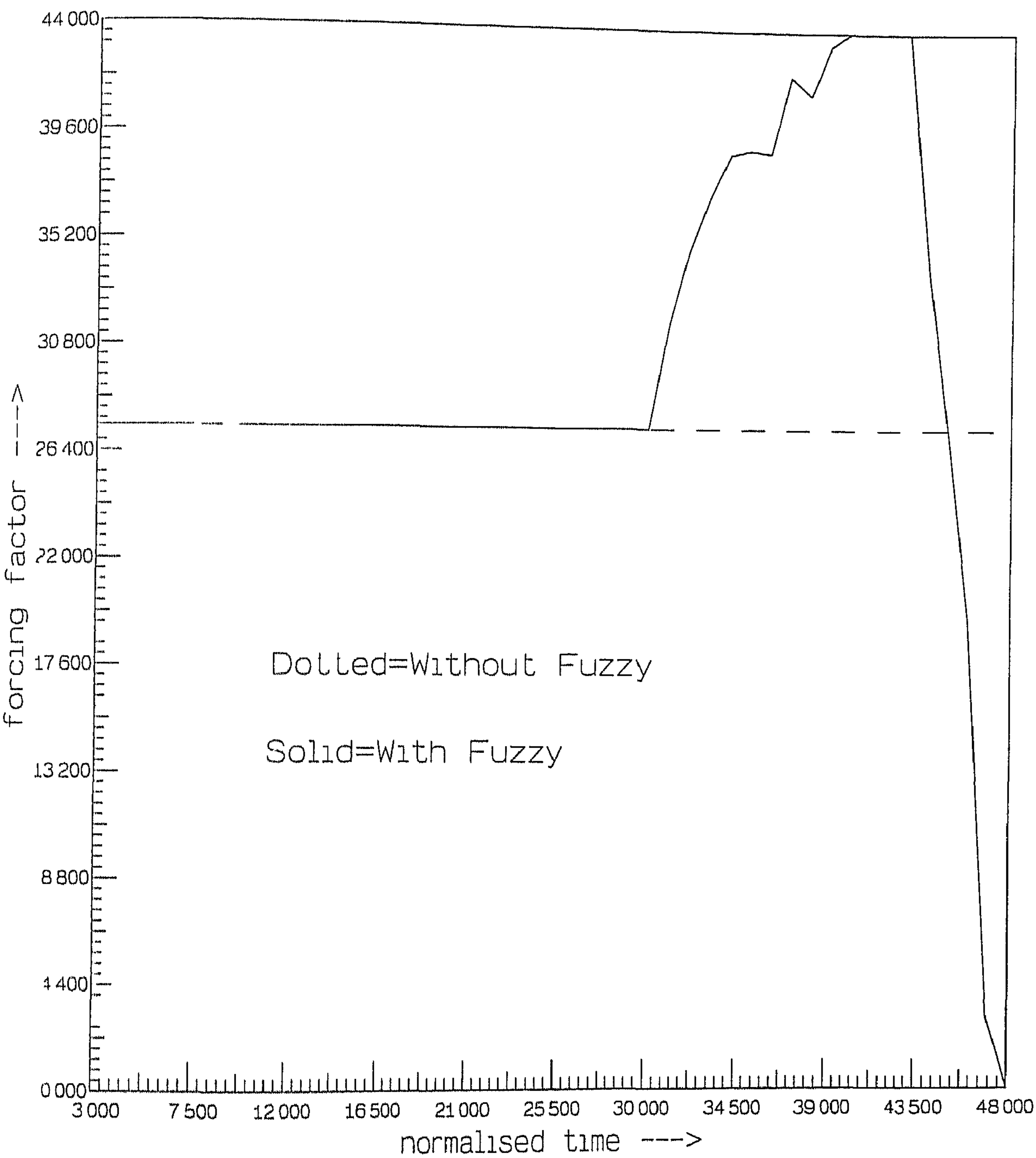

Figure 4 13 Variation of peak acceleration with time

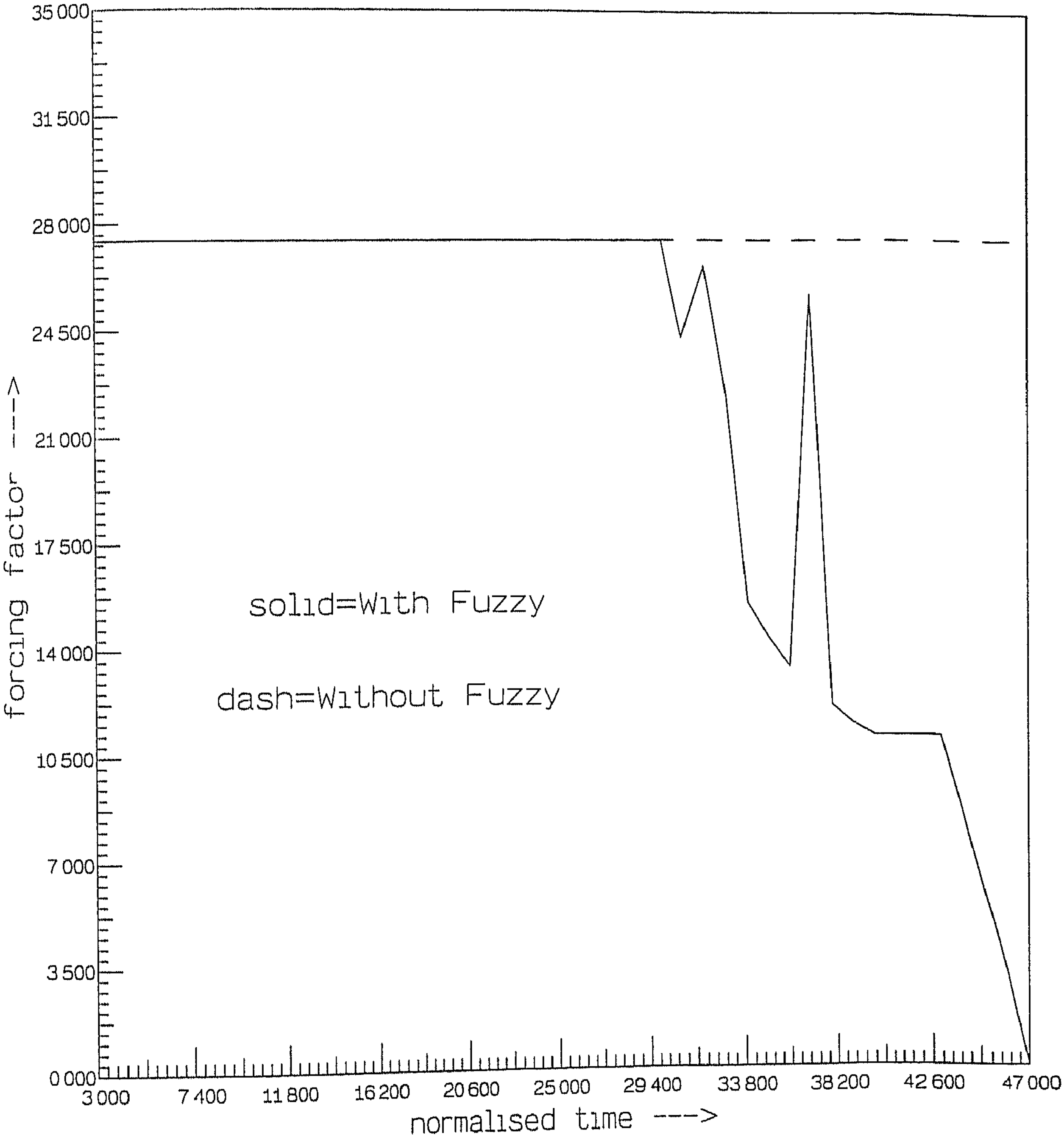

Figure 4 14 Modified curve showing variation of acceleration with time

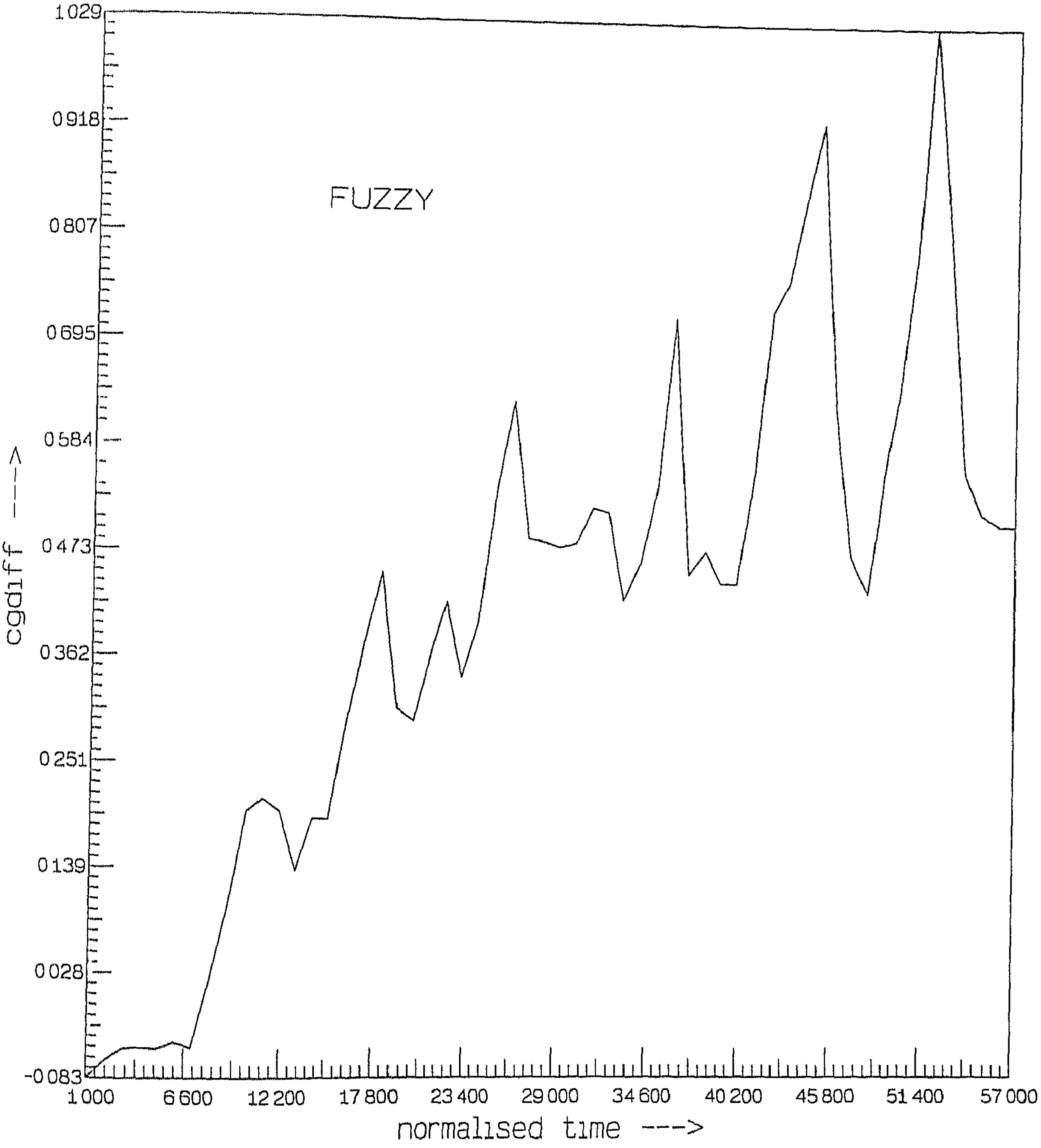

Figure 4 16 Curve showing variation of cgdiff with Fuzzy application

The controller is used to study the separation behavior of a bed as described earlier The results of simulation is shown in figure 4 16 The theoretical *cgdiff* was calculated as 0 576-m This *cgdiff* unlike before is the difference in the center of gravity of the heaviest particles of one density class with that of other The cgdiff obtained with a little change in the membership functions is 0 501 This is an indication that the use of the controller can be extended to real system with very little computational effort

4.4 Computer Animation

A computer program is also available for visualization of numerical data This program assists in visual assessment of the correctness of the process Different snapshots are taken to compare the degree of stratification with and without the use of the controller These snapshots are shown in figure 4 17 through 4 20 The first two snapshots as in figure 4 17 and 4 18 show the state of the bed at the beginning and end of jigging The amplitude and frequency of pulsation that gives maximum *cgdiff* is employed Figure 4 19 and 4 20 correspond to a jigging condition where the controller is used

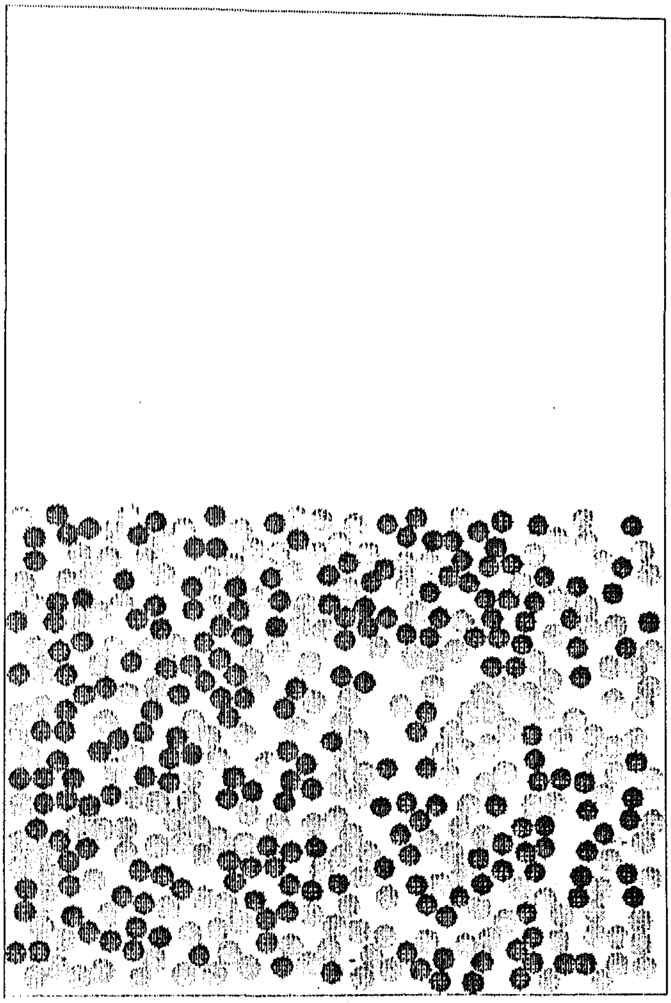

Figure 4.17: Position of the bed at the beginning of stratification

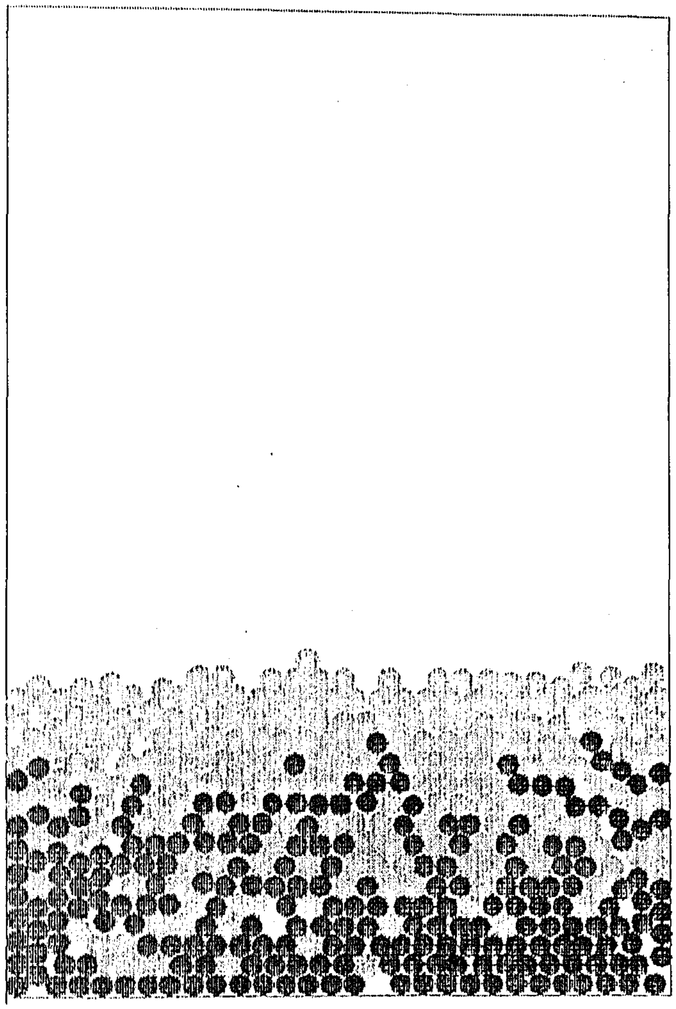

Figure 4.18: Position of the bed at the end of stratification

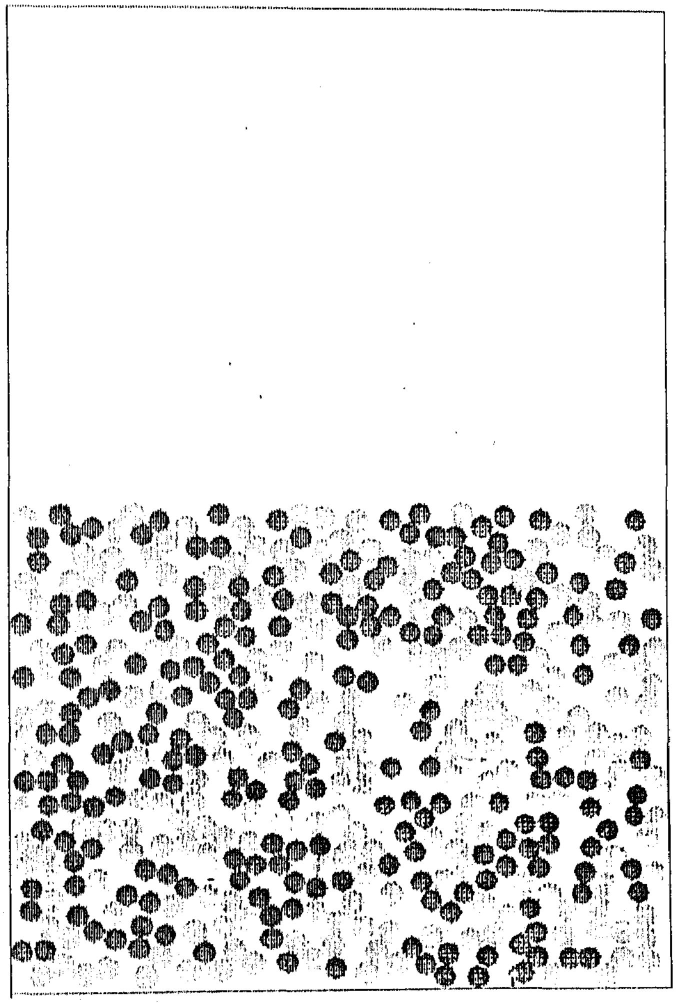

Figure 4.19: Position of the bed at start, with Fuzzy application

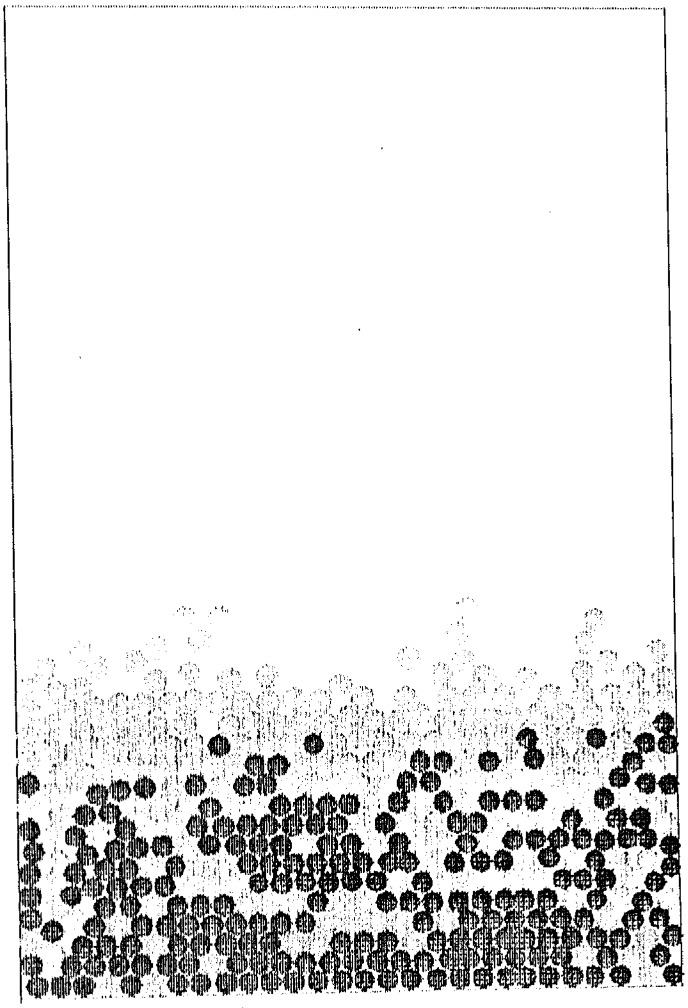

Figure 4.20: Position of the bed at end, with Fuzzy application

Chapter 5

CONCLUSIONS

In this thesis a systematic investigation into the stratification phenomena taking place during jigging is made with a view to develop a controller that can be used to improve the process performance. It is widely believed that the stratification of particles is a complex phenomena and very little is known about the micro-mechanics of the process. Therefore, the mathematical models that are available to analyse the jigging process often suffer from empericism and gross simplifications. In this work a well established mathematical model developed by Tavares and King [7] is used to study the stratification phenomena. However, the inherent shortcomings of the model precluded its use as a simulator for process analysis. A more robust computer program based on the discrete element method [11] is used is considered in this study. For the results of DEM model is compared with that of Tavares and King model[7] and found to be quite satisfactory.

A brief literature review of jigging process is done to understand the basic mechanism of jigging. Although there are many theories available that explain the jigging process, only Tavares and King model[7] and DEM model were studied in detail. While the DEM model was used as a substitute for the actual process, the Tavares and King model[7] was used to validate the results obtained by the former model. Both the models were used to predict the degree of stratification of a jig bed comprising of 3 types of particle only varying in density. The α-value prdicted by both the models are quite comparable. This factor α relates the

degree of stratification to process parameters as explained in the Tavares and King model. Tavares and King model has been validated against experimental data and since the results of DEM and Tavares and King model matched, it is believed that the DEM model can be used successfuly for process analysis.

Main objective of the thesis is to the develop a controller and it is at this end a brief review of the theory of fuzzy logic control is presented. It is found that fuzzy control is easy to understand and amenable to computer implementation. Before applying this theory, the control parameters were identified as amplitude and frequency of pulsation and the variables to be controlled for better stratification were identified as *cgdiff.*

Various simulations were carried out using the simulator developed based on DEM model. The simulation results are analysed by studying the variation of *cgdiff* with *time.* The results show that for any simulation with fixed amplitude and frequency the *cgdiff* increases with increase in time at the beginning, and then reaches a peak value before falling back to zero. The *cgdiff* at the end of stratification is obtained when the bed is in a dynamic as well as static state. The peak value is the maximum *cgdiff* that can be achieved under the simulated pulsation conditions.

The results of simulation done at different pulsation rates show that the variation of peak *cgdiff* with frequency and amplitude is parabolic in nature. The reason for this behavior is that at lower frequencies the dilation of the bed at a any amplitude is less that allows insufficient time for the particle to readjust. Thus ther is a poor separation. The *cgdiff* increases with increase in frequency and reaches a peak value. The frequency at which this value is achieved is the best operating frequency. The *cgdiff* at this pulsation rate shows the minimum potential energy condition of the jig bed according to Mayer[6]. Further increase in frequency disturbs an already stratified bed because the energy through pulsation is unable to decrease the potential energy any furthur as it has already reached the minimum condition.

It is also observed that the energy required to sustain the stratification process increases with increase in both frequency and amplitude. For higher values of frequencies the trend is somewhat different: Here the energy decreases with increase in frequency beyond a critical amplitude. All this information is graphically presented by means of a 3D-Plot to show the best operating condition.

Fuzzy rules were formulated based on the simulation results and the stratification process is carried out with the application of the rules. It is observed that the required *cgdiff* is achieved within less span of time. The amount of reduction in energy consumption with the application of fuzzy logic control when calculated was observed to be 20%. This observation shows that the stratification done with fuzzy logic control leads to reduced energy loss with simultaneous increase in yield, proving fuzzy logic control as a viable control technique for analysing such complex nonlinear process.

The analysis is furthur extended by taking six types of particles differing in size and density. The controller is tuned for this system and the results show that fuzzy logic controller is able to drive the process to the desired level of stratification.

Finally, based on this study, it is believed that for a process like jigging which is conceived as a complex one, any improvement in its performance can only mate through proper control. At this end, fuzzy logic approach is not just another way but should be considered owing to its proven advantages. It has been found to be quite simple to understand and implement.

Suggestions for Future Scope of Work

Above discussion made on the utility of fuzzy logic control has some drawbacks too. Fuzzy logic control entirely depends on the human experience for forming the rule base, which may not be perfect due to human error. The derivation of an adequate set of rules and its representation in a form suitable for use is difficult in a dynamic process. This is because fuzzy logic control attempts to implement the human decision making allowing the

subjective and qualitative knowledge, but it lacks the important learning characteristics The reason for this being that while human ability has the capacity to learn from his experience and apply it to modify the control action such that better results can be achieved, the fuzzy rules once formulated cannot be debugged for better results

This drawback of fuzzy logic control can be overcome Processes can be controlled by implementing an online control with the modification of the fuzzy rules which is defined as *self organizing fuzzy controller* Self organizing controller adds a supervisory level to the fuzzy controller such that the fuzzy rules are modified dynamically to have better results This addition of a supervisory level has two functions a) analysing the output obtained by old fuzzy rules by calculating the error and b) predicting the performance rules to be applied

In the present thesis, control of stratification process taking place in jig with the help of fuzzy logic controller is done by only considering the major control parameters i e , amplitude and frequency But certain other factors like variations in the feed rate of the mineral, compressor pressure, etc , may also be required to be controlled in order to achieve better results Thus simulataneous control of all these parameters together with the help of self organizing controller would definitely lead to better stratification results close to that of theoritical values

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